Université du Québec
à Rimouski

Intégration de la réalité augmentée et la réalité virtuelle dans le domaine de la maintenance industrielle des systèmes électromécaniques

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Pour A. qui prie pour moi, Pour K. qui me garde en pensées, H. qui me protège, N. qui me supporte, I. qui m’aime et M.O.S.N.S qui m'encouragent

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RÉSUMÉ

Des nouvelles perspectives de maintenance ont été introduites à l'ère de l'industrie 4.0 ou le concept de maintenance 4.0. Ce concept est basé sur la flexibilité et l'adaptation. C'est un système qui adapte les lignes de production pour être flexible en agissant sur les actifs dans différentes perspectives de plan d'utilisation et de disponibilité. Les nouvelles technologies ont un effet considérable sur les industries d'aujourd'hui. Elles ont introduit une nouvelle ère de systèmes de gestion de production et maintenance. La réalité augmentée (RA) est une technologie qui superpose des éléments virtuels, tels que des images, des vidéos ou des informations, sur le monde réel, généralement à travers un dispositif comme les tablettes, les smartphones ou des lunettes spéciales. La réalité virtuelle (RV) est une technologie qui permet à l'utilisateur d'entrer dans un environnement entièrement virtuel, généralement à l'aide d'un casque spécialisé. La RA et la RV sont parmi plusieurs technologies utilisées pour le même objectif. Aujourd'hui, une intégration de ces technologies est rendue un investissement rentable afin d'avoir un plan de maintenance efficace. Le but de cette étude est d'explorer les deux grandes technologies, la RV et la RA, en les combinant avec les exigences de maintenance en termes de plan, outils et cadre d'utilisation. Pour mener bien à cette étude, des analyses ont été faites concernant l'efficacité d'intégration de la RA et la RV en validant les conditions des piliers d'instauration (Logiciels, Matériels, interface d'utilisation…) et en mettant en évaluation l'effet sur l'utilisateur, les indicateurs de maintenance, les améliorations futures et le leur implication sur le volet de santé et sécurité. Cette démarche part de l'hypothèses que les méthodes d'application des interventions de maintenance ne sont plus suffisantes pour une rentabilité élevée en respectant les taux de production de nos jours. À cet effet, plusieurs méthodologies ainsi que des architectures de systèmes sont proposées dans le cadre de la recherche en mettant en œuvre les situations et les cas d'utilisation pour chaque technologie pour assurer une instauration complète et structurée. Ces méthodologies sont conçues en respectant les fonctionnalités et le cadre des différents situations et secteurs (secteur minier comme exemple). Pour mettre en évidence les cadres d'application proposé, plusieurs outils sont exploités pour élaborer le cadre théorique ainsi que les conceptions utilisées tels que les logiciels Unity 3D, Solidworks, Blender, 3DsMax, etc. Les conclusions de la recherche ont également pointé l'aspect rentable et prometteurs des méthodologies adoptées pour un effet concret sur les utilisateurs de ces outils (les opérateurs et experts de maintenance) ainsi que les effets sur le domaine de maintenance elle-même comme entité très essentielles dans les industries.

Mots clés : Maintenance intelligente, Réalité virtuelle, Réalité augmentée, santé et sécurité, Production, secteur minier, Unity 3D.

ABSTRACT

New maintenance perspectives have been introduced in the era of Industry 4.0, or Maintenance 4.0. This concept is based on flexibility and adaptation. It's a system that adapts production lines to be flexible by acting on assets in different perspectives of utilization plan and availability. New technologies are having a considerable effect on today's industries. They have ushered in a new era of production and maintenance management systems. Augmented reality (AR) is a technology that superimposes virtual elements, such as images, videos or information, on the real world, usually through a device such as a tablet, smartphone or special glasses. Virtual reality (VR) is a technology that allows the user to enter a fully virtual environment, usually through a specialized headset. AR and VR are among several technologies used for the same purpose. Today, the integration of these technologies has become a cost-effective investment in an efficient maintenance plan. The aim of this study is to explore the two main technologies, VR and AR, by combining them with maintenance requirements in terms of plan, tools and framework of use. To carry out this study, analyses were carried out on the effectiveness of AR and VR integration, validating the conditions of the implementation pillars (software, hardware, user interface, etc.) and evaluating the effect on the user, maintenance indicators, future improvements and their implications for health and safety. This approach is based on the assumption that the methods used to apply maintenance interventions are no longer sufficient to ensure high profitability while respecting today's production rates. To this end, several methodologies and system architectures are proposed as part of the research, based on the situations and use cases for each technology, to ensure a complete and structured implementation. These methodologies are designed with respect to the functionalities and framework of different situations and sectors (mining sector as an example). To highlight the proposed application frameworks, several tools are exploited to elaborate the theoretical framework as well as the designs used, such as Unity 3D, Solidworks, Blender, 3DsMax, etc. The conclusions of the research also pointed to the cost-effective and promising aspect of the methodologies adopted for a concrete effect on the users of these tools (operators and maintenance experts) as well as the effects on the maintenance field itself as a very essential entity in industries.

Keywords: Smart Maintenance, Virtual Reality, Augmented Reality, Health and Safety, Production, Mining, Unity 3D.

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AR	Augmented reality
XR	Extended reality
MR	Mixed reality
CC	Cloud computing
CPPS	Cyber-physical production systems
IoT	Internet of things
PDM	Predictive maintenance
CBM	Condition-based maintenance
TBM	Time-based maintenance
MTTF	Mean time to failure
MTTF	Mean time to failure
CCEB	Current condition evaluation-based
FCPB	Future condition prediction-based
FCPB	Future condition prediction-based
RUL	Remaining useful life
NDT	Non-destructive testing
CPS	Cyber-physical systems

IoS	Internet of systems
ML	Machine learning
DL	Deep learning
HMI	Human machine interface
AI	Artificial inteligence
HMD	Head mounted device
HHD	Handheld display
FOV	Field of view
SDK	System development kit
CAD	Computer aided design
SLAM	Simultaneous localization and mapping
PLM	Product life management
MRO	Maintenance, repair and operations
KPI	Key performance indicators
PSS	Product service system
IM	Information mappinng
STE	Simplified technical english
CNL	Controleled natural language
DITA	Darwin information typing architecture
XML	Extensible markup language

GUI	General user interface
SME	Small and midsize entreprise
DG	Design guidelines
SQL	Structured query language
API	Application programming interface
VE	Virtual environment
CAVE	Cave automatic virtual environment
MTR	Mean time to repair
SOP	Standard operating procedure
MTBF	Mean time between failures
TRS	Synthetic rate of return
TRG	Overall rate of return
WI	Work instruction
BOYD	Bring your own device
LMP3	Laboratoire des matériaux, produits et procédés de pointe
OEM	Original equipment manufacturer

LISTE DES SYMBOLES

HP	Horse Power
V	Volt
A	Ampère
kVA	kilovoltampère

INTRODUCTION GÉNÉRALE

1. CONTEXTE ET GENERALITES :

L'industrie manufacturière a toujours été soumise à des changements importants depuis le début de la première révolution industrielle, qui a vu l'introduction de la vapeur et de la production mécanisée. La deuxième révolution industrielle a introduit les chaînes de montage et l'électricité dans les entreprises. L'introduction de l'automatisation dans les années 1970 a déclenché une troisième vague de révolution industrielle. Une nouvelle révolution industrielle sera alimentée par des initiatives telles que l'industrie 4.0 et d'autres du même type, qui encouragent à intégrer la technologie numérique dans l'environnement de fabrication. Cela permettra la création d'un système de production intelligent.

La réalisation de l'intelligence dans l'industrie manufacturière du futur dépendra de l'adoption généralisée des technologies numériques. Les termes réalité augmentée (RA), réalité virtuelle (RV), maintenance prédictive (PM), cloud computing (CC), internet des objets (IoT), big data, et jumeaux numériques sont tous des exemples de technologie numérique. L'utilisation des technologies numériques permet de collecter des données et de créer des informations pour atteindre des sommets auparavant inatteignables. Développer des systèmes de production cyber-physiques (CPPS) qui connectent le monde physique et le monde numérique de manière transparente dans le but de rendre la fabrication plus intelligente et, par conséquent, d'améliorer l'adaptabilité (autonome), l'autonomie et la flexibilité, tel est l'objectif de l'initiative Industrie 4.0. Malgré le fait que l'accent soit mis sur la technologie, les humains restent une partie essentielle du processus de production.

D'autre part, dans les processus industriels, l'entretien régulier des équipements est l'un des éléments les plus importants. La maintenance des équipements est essentiel en tant qu'élément intégral du cycle de vie de la production, elle représente de 15 à 60 % du coût global de la production [1]. Par conséquent, la capacité à anticiper les activités de maintenance des machines et à les réaliser en peu de temps peut conduire à un dépannage réussi, ce qui, à son tour, peut simultanément augmenter la disponibilité des équipements. En outre, étant donné que le coût du remplacement des composants endommagés peut représenter jusqu'à 70 % du coût total de la maintenance [1], il est de la plus haute importance pour les entreprises manufacturières de trouver des stratégies alternatives pour réduire le coût de la maintenance afin d'augmenter leurs bénéfices globaux. Cela a pour conséquence directe d'améliorer le niveau de performance de l'ensemble de la production [2].

Les technologies interactives de la RA pour la maintenance aident les opérateurs au niveau de l'atelier et fournissent à l'utilisateur d'une application RA une grande quantité d'informations contextuelles facilement compréhensibles. La technologie de la réalité augmentée jouera un rôle essentiel dans le fonctionnement des futures usines [3]. Aujourd'hui, la grande majorité des applications de réalité augmentée dans le domaine de l'ingénierie du cycle de vie (TES) sont utilisées pour l'inspection ou la maintenance (24 % et 54 % respectivement) [4]. En outre, l'une des difficultés des applications de réalité augmentée est qu'elles ont tendance à être statiques en raison de l'importance du travail de préparation nécessaire. Une approche pour une application dynamique et intelligente de la RA permettrait d'améliorer l'état de l'art en matière de développement de la RA pour la maintenance.

Quant à la RV en maintenance, qui est l'une des technologies utilisées dans l'usine numérique, peut être caractérisé comme un environnement créé par l'utilisation de la technologie informatique pour créer l'effet d'un monde interactif en 3D dans lequel les choses ont un sentiment de présence spatiale [5]. Cet environnement peut être décrit comme un monde virtuel dans lequel les objets ont le sentiment de leur propre présence spatiale. Il est largement reconnu comme une progression logique de l'infographie 3D. Cette approche a progressé au point de pouvoir désormais garantir des applications pratiques dans le secteur industriel. Plusieurs types d'applications de fabrication, notamment la conception, l'ingénierie, la fabrication, les opérations et la maintenance, peuvent tous bénéficier de l'utilisation de la technologie de la réalité virtuelle en conjonction avec des systèmes logiciels modernes. La combinaison de la réalité virtuelle et des opérations industrielles offre l'assistance essentielle pour construire un système de production à la fois rentable et doté d'une gestion avancée de la maintenance. Elle est considérée comme une plateforme de formation viable pour les opérations industrielles et les emplois de maintenance relativement compliqués et exigeants.

L'utilisation d'un système de maintenance virtuelle pour la formation en maintenance qui fait appel à la technologie de la réalité virtuelle s'est avérée offrir une variété d'avantages qui ne sont pas présents dans les systèmes de formation et de maintenance conventionnels. Il fournit une formation à la maintenance critique en utilisant l'approche de l'apprentissage par la pratique, ce qui n'est pas réalisable dans un contexte réel en raison de limitations telles que le coût, le temps et la sécurité, entre autres. En outre, un système de maintenance virtuel facilite le processus de formation en utilisant des éléments visuels, sonores ou tactiles. Il permet également de simuler la tâche sous une forme suffisamment flexible pour s'adapter aux exigences des utilisateurs et aux objectifs de formation qu'ils souhaitent atteindre [6].

La gestion des opérations industrielles et de la maintenance est un système complexe composé d'un grand nombre d'éléments humains et mécaniques qui dépendent les uns des autres. Il a été établi que la technique essentielle d'intervention pour améliorer la qualité et la fiabilité du processus de maintenance industrielle consiste à fournir aux participants une formation approfondie. Il est absolument nécessaire d'offrir aux opérateurs les outils et l'environnement appropriés pour que la formation soit couronnée de succès. Dans ces conditions, l'application de la technologie de la RV à des fins de formation en maintenance a le potentiel de produire une valeur ajoutée.

L'industrie minière est extrêmement importante pour l'économie globale car elle est responsable de la production de ressources cruciales. Cependant, l'industrie minière est également confrontée à des problèmes particuliers en termes de sécurité, de productivité et de maintenance. La maintenance est un élément essentiel des opérations minières, car elle garantit le bon fonctionnement de toutes les machines. L'application de la technologie de la

RV peut participer positivement au développement des opérations dans le secteur minier. Il est urgent de réduire les dépenses liées à la maintenance, et la réalité virtuelle (RV) offre une solution sous la forme d'une formation virtuelle immersive qui permet aux employés de maintenance de pratiquer des procédures dans un environnement qui est à la fois sûr et sous contrôle. Cette approche réduit le nombre d'erreurs, favorise le développement des compétences et augmente la fiabilité des équipements. D'autre part, la réalité virtuelle a le potentiel d'améliorer considérablement la sûreté et la sécurité sur le lieu de travail en permettant aux travailleurs de participer à des inspections virtuelles, à l'identification des dangers et à la formation à l'intervention d'urgence sans se mettre en danger. L’environnement de réalité virtuelle facilitent également l'adoption de normes de sécurité strictes et renforcent la conscience de la situation, ce qui réduit la probabilité d'accidents et améliore la sécurité au milieu de travail. Pour répondre aux besoins de cette application de l'industrie minière, notre projet utilisera principalement le logiciel Unity 3D pour développer un environnement virtuel personnalisée pour l'unité de maintenance de l’unité de forage.

2. RA ET LA RV DANS LA MAINTENANCE 4.0 :

L'introduction de l'industrie 4.0 et son développement remarquable au cours des deux dernières décennies ont matérialisé des changements rapides susceptibles de lever plusieurs barrières au sein des unités industrielles. La maintenance industrielle est un domaine dans lequel les technologies de l'information jouent un rôle de plus en plus important. Le concept de réalité mixte (RM) élargit les possibilités des pratiques classiques en exposant l'utilisation de données multimodales médiatisées par ordinateur dans un environnement virtuel immersif ou en tant qu'augmentations dans le monde réel. D'un côté, la RV s'est avérée être un environnement viable pour la formation en raison de la flexibilité et du réalisme de l'expérience, en plus de la possibilité de simuler en toute sécurité des opérations et des contextes dangereux. D’autre part, l’assistance sur le terrain via la RA peut améliorer la rapidité, la qualité et la sécurité du travail, ce qui se traduit par une diminution de la charge de travail physique et mentale des techniciens.

2.1 RA un outil indispensable dans la télémaintenance :

Plusieurs facteurs majeurs ont poussé les recherches dans la maintenance intelligente. L'acquisition et l'analyse des données, le stockage, la distribution, la sécurité et l'intelligence ont eu une importance dans le lancement d'une telle maintenance par les groupes de recherche. Comme déjà mentionné, un taux de 15% à 60% est le coût exploité par la maintenance au sein des entreprises manufacturière [1]. Ainsi, un tel résultat justifie en plusieurs perspectives le besoin d'étude sur la manière de déployer les nouvelles technologies.

En effet, Pour une bonne rentabilité, qualité de produit et accessibilité on mentionne toujours ces raisons : le besoin constant d'amélioration en termes de temps, d'erreurs, de sécurité et de coûts. Ces facteurs justifient l'utilisation de la technologie de la RA. Une intégration de la RA dans un champ d'application porte un effet concret tout dépendamment des besoins et des conditions d'application.

Les interventions de maintenance en industrie sont faites pour assurer une amélioration continue des composants, minimiser le temps d'opération et optimiser par la suite la durée de vie utile du composant. Les tâches et les opérations les plus connue et courantes tout au long de la ligne de fabrication sont divisées en quatre catégories principales :

1. Assemblage et démontage ;
2. Réparation ;
3. Diagnostic ;
4. Formation.

Toutes ces catégories peuvent être plus efficace en termes de mise en œuvre et application des interventions en exploitant plusieurs systèmes d'information et technologies comme la RA. De nos jours, parmi plusieurs cas, il est possible d'imaginer un scénario dans lequel un opérateur local inexpérimenté effectue la maintenance sous la supervision d'un opérateur qualifié relié à distance : la télémaintenance. En réduisant la nécessité pour les opérateurs qualifiés de se déplacer, cette approche permettrait de réduire les coûts de maintenance tout en augmentant la qualité du service grâce à leur intervention rapide. Les entreprises s'intéressent aux dernières avancées en matière de technologie mobile parce qu'elles permettent l'intervention à distance, ce qui améliore le service de maintenance et réduit les dépenses d'exploitation. Les principales exigences pour l'application de télémaintenance, basées sur plusieurs expériences, sont les suivantes :

- L'application doit permettre aux deux opérateurs, experts et non experts, de communiquer aisément afin qu'ils puissent identifier, sur la base du problème rencontré, la partie du système qui doit être réparée ou corrigée. Cette communication peut être verbale (dans le cas où ils parlent la même langue) ou basée sur l'échange d'images ou d'informations symboliques.

- Une fois le diagnostic effectué et les pièces à réparer identifiées, l'opérateur qualifié doit être en mesure d'indiquer avec précision l'opération et l'endroit où la réaliser. L'application de RA doit afficher les informations numériques dans le contexte réel, avec précision.

- L'opérateur qualifié doit être en mesure de vérifier si l'opération de maintenance a réussi ou non. L'application doit permettre à l'opérateur qualifié de suivre l'évolution de la tâche de réparation.

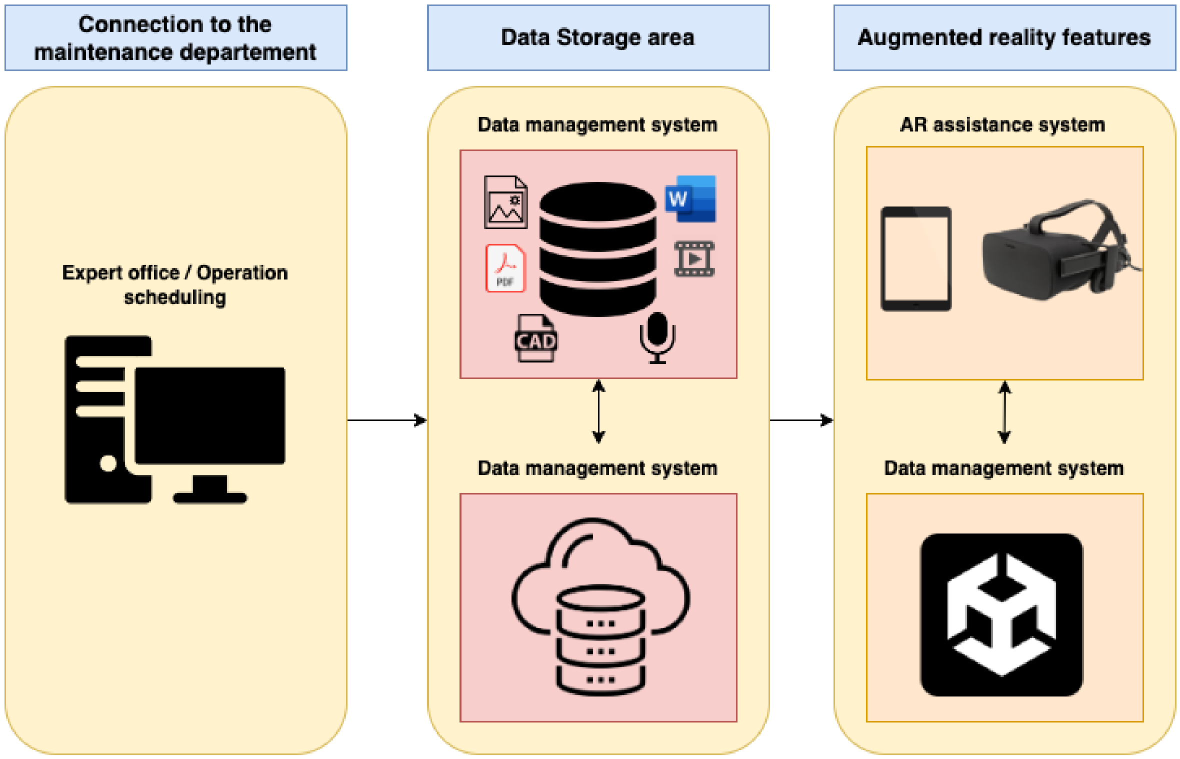

Figure 1: La structure générale d'un système de télémaintenance

2.2 RV pour la formation des opérations de maintenance :

La technologie de la RV assure un environnement interactif tridimensionnel. Cet environnement fournit un moyen unique d'amélioration de la visualisation d'objets tridimensionnels complexes et offre davantage plus de capacités interactives et spatiales. L'application de la RV aux processus de fabrication ainsi qu'au développement de produits et de processus peut conduire à des temps de développement plus courts, à des coûts réduits et à une qualité améliorée. L'objectif de la RV est de créer un système aussi parfait que le monde réel, voire meilleur et plus efficace.

La RV est utilisée avec succès dans des applications de formation virtuelle, où un opérateur d'usine virtuel utilise un environnement 3D réaliste basé sur des données. Dans cet environnement de formation, des lunettes de réalité virtuelle sont utilisées pour former le personnel de l'usine à gérer les situations d'urgence. D'Ailleurs, les utilisateurs et les opérateurs peuvent placer les informations de fabrication nécessaires dans leur champ de vision en utilisant ce dispositif. Les lunettes utilisent la réalité virtuelle pour mettre en évidence l'endroit où chaque composant d'une machine ou d'un équipement doit être entretenu.

Les opérations et la maintenance virtuelles nécessitent l'intégration de multiples domaines et il est important de synchroniser les technologies connexes pour permettre les applications industrielles de la maintenance virtuelle. Il est prévu que le système de RV converge vers un nouveau système de maintenance dans un environnement de fabrication virtuel ou autre. Cet environnement virtuel permettra à l'ingénieur de maintenance d'entretenir virtuellement le produit pour le rendre opérationnel. Le système de maintenance virtuelle offre une formation et un apprentissage pertinents à l'ingénieur de maintenance d'une manière simple et flexible.

L'utilisation d'un système de maintenance virtuelle faisant appel aux technologies de la réalité virtuelle s'est avérée offrir une série d'avantages par rapport aux systèmes de formation et de maintenance traditionnels. Elle offre la formation nécessaire à la maintenance selon l'approche de l'apprentissage par la pratique, ce qui n'est pas possible dans un environnement réel en raison de limitations telles que le coût, le temps, la sécurité, etc. En outre, le système de maintenance virtuelle facilite le processus de formation grâce à des éléments visuels, auditifs ou haptiques. De plus, ce système permet de simuler la tâche de manière flexible afin d'adapter les exigences des utilisateurs et les objectifs de la formation.

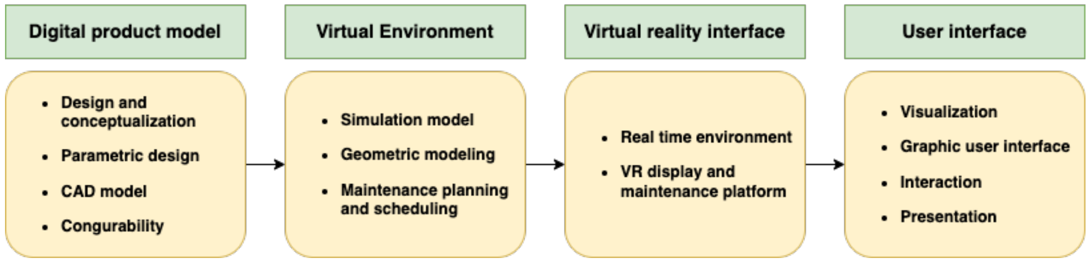

Figure 2: Étapes globales de développement d'un système de réalité virtuelle

3. PROBLEMATIQUE :

En raison du coût croissant des techniciens spécialisés, de la complexité grandissante des travaux de maintenance et de la criticité croissante des longs temps d'arrêt des machines, la réalité augmentée (RA) joue un rôle de plus en plus important dans la maintenance avancée et assistée à distance. Dans de nombreux cas, les applications de service industrielles modernes nécessitent des interventions spécialisées, et les programmes d'apprentissage sont coûteux et prennent beaucoup de temps. Les nouveaux employés ont besoin d'être supervisés sur place par des techniciens plus expérimentés, ce qui entraîne une augmentation des coûts et complique le modèle de travail, compromettant ainsi l'efficacité et l'efficience du service. On peut citer quelques mesures traditionnelles prises par les différentes entreprises comprennent :

- Des appareils classiques qui permettent aux techniciens de communiquer entre eux et avec le service de maintenance ;
- L'accès à des tableaux de bord et à des rapports détaillés ;
- L'utilisation des anciens personnels pour intégrer les nouveaux opérateurs.

Aujourd'hui, cependant, ces solutions ne sont pas suffisantes en elles-mêmes : déployer les aspects ergonomiques, assurer la facilité d'utilisation, et la nécessité de fournir des informations pertinentes et contextuelles aux techniciens. L'ensemble du système peut être rendu plus efficace en adoptant des modèles modernes qui permettent l'assistance utile de travailleurs expérimentés même lorsqu'ils ne sont pas physiquement présents sur le site et qui offrent des conseils à un plus grand nombre d'apprentis en même temps. La capacité du département de maintenance et d'ingénierie à communiquer efficacement avec les opérateurs sur le terrain devient de plus en plus importante pour le fonctionnement d'une approche de maintenance réussie. Dans cette vision, la RA élabore une communication plus rigide entre les différents actionneurs de maintenance experts vers l'opérateur débutant. D'ailleurs, Une instauration de ces genres de solutions sont dans le périmètre d'applications de l'industrie 4.0. Aujourd'hui, les sites industriels et les unités de production ne sont pas installés dans les mêmes emplacements en termes de localisation physique. De ce fait, une telle problématique nécessite une approche de déploiement d'un moyen à distance pour la mise en œuvre des interventions de maintenance en agissant par la suite sur les différents taux et les indicateurs de maintenance et les temps d'arrêt et disponibilité. Ici, on parle de l'impact de la RA sur la précision et la rapidité des réparations dans le cadre de la télémaintenance. D'autre part, des telles solutions restent insuffisantes en présence de machines et d'équipements variés, ainsi que la nécessité d'interopérabilité avec d'autres systèmes, logiciels utilisés dans l'industrie, des conditions de travail difficiles et les contraintes de sécurité (le cas du secteur minier comme exemple).

De ce fait, il est nécessaire d'élaborer un plan d'action pour déployer une solution de mise en œuvre des opérations de maintenance dans un environnement sécuritaire, contrôlé et qui répond aux exigences de réalisme et du milieu de travail réel. La phase de formation des opérateurs et des différents personnels d'une unité industrielle est une étape cruciale pour l'introduction de chaîne de production. Sauf que dans une telle phase, et par le manque d'expérience, le nouvel opérateur est exposé face à des situations de risque, d'où la nécessité d'une solution pour éliminer toutes les possibilités d'accident du personnel. À cet égard, l'utilisation d'un environnement virtuel comme première expérience avant d'entamer les opérations de risques est une solution bénéfique. La RV est utilisée avec succès dans la formation virtuelle, où un opérateur d'usine virtuel utilise un environnement 3D réaliste. Dans cet environnement de formation, des appareils sont utilisées pour former le personnel de l'usine et gérer les situations d'urgence. Les travailleurs humains sont équipés de lunettes de réalité virtuelle ou tout simplement des téléphones intelligents qui peuvent placer les informations de fabrication nécessaires dans leur champ de vision.

Dans un contexte plus précis, l'intégration de la RA et la RV se différencie selon le domaine d'application. Le secteur minier présente plusieurs facteurs qui perturbe l'application efficace de ce genre de technologies par rapport au secteur manufacturier. Ces facteurs sont principalement : la poussière, le bruit sonore, la luminosité et l'emplacement des éléments de production (outillage, équipement …). Ils affectent le fonctionnement normal des dispositifs d'interaction de la RA et la RV. Quant au secteur manufacturier, il est moins compliqué de faire une instauration totale et efficace des applications de la RA et la RV. Cela est due au nature de l'environnement qui assure un champ visuel et auditif plus nette.

L'utilisation des technologies de RA et RV révolutionnent la formation des opérateurs de maintenance, en leurs permettant d'acquérir des compétences plus rapidement et dans un environnement plus sécurisé. En outre, le développement de ces technologies ouvre de nouvelles perspectives dans le domaine de la télémaintenance. Ces technologies comprennent désormais des outils visuels et interactifs qui peuvent aider le personnel à distance à effectuer ses tâches de maintenance. La maintenance des unités industrielles peut-être ainsi plus efficace, plus performante et plus réactive, tout en étant plus rentable.

4. OBJECTIFS :

Le but de ce mémoire est donc d'explorer les deux grandes technologies, la RV et la RA, en les combinant avec les exigences de maintenance en termes de plan, outils et cadre d'utilisation afin d'optimiser cette entité pour mieux comprendre les résultats antérieurs et être capable de prédire les résultats futurs. Pour atteindre ces objectifs, il est nécessaire de passer par des sous-objectifs qui correspondent à des étapes spécifiques du projet de recherche.

Le premier objectif se présente comme une approche littéraire de la technologie de la RA ainsi qu'à son utilisation dans l'industrie 4.0 et plus spécifiquement la maintenance. Il a pour but de présenter dans un premier temps la maintenance intelligente et ces différents outils, les avancées de la réalité augmentée, son effet sur la maintenance en présentant les nombreuses applications développées dans plusieurs domaines, et aussi les piliers de cette technologie et les développements futures pour chacun de ces piliers. Cet objectif est essentiel pour l'exploration et les recherches futures que l'on vise.

Le second objectif vise à étudier et présenter une approche d'implémentation de la RA dans la maintenance comme outils d'intervention à distance. Il s'agit d'une méthodologie d'instauration d'une application de communication pour mise en œuvre des opérations de maintenance entre experts et opérateurs. On vise ainsi par ce travail de mettre en place la bonne structure de communication et le cadre de travail pour obtenir par la suite un support efficace entre les experts et les opérateurs. De plus, un autre objectif visé est d'exploiter tous les outils de la même technologie en proposant la bonne démarche d'instauration des piliers (logiciels, matériels, Interface d'utilisateur…).

Le dernier objectif a pour but d'étudier et de concevoir un environnement comme première étape de mise en place d'une application de réalité virtuelle dans le contexte du secteur minier. Ce travail vise à bien intégrer les exigences d'un atelier de maintenance sur le plan de procédure de maintenance, des équipements utilisés et la nature des interventions. D'autre part, on vise ainsi à bien accomplir la mission de conception des modèles 3D utilisés en gardant en considération le paramètre de réalisme. Une autre motivation pour ce travail est d'assurer les conditions de santé et sécurité des opérateurs de maintenance vu les circonstances du milieu de forage pétrolier pour pratiquer les interventions de maintenance. L'environnement va permettre de valider la première étape d'instauration avant d'exporter l'application.

5. METHODOLOGIE :

La première phase du travail consiste à déterminer les avancements effectués dans le domaine de la maintenance 4.0 ainsi que la réalité augmentée. En effet, le premier article est sous forme d'une revue de littérature qui regroupe la majorité des travaux réalisés dans le domaine de la réalité augmenté, en présentant les différents piliers et exemples d'applications de cette technologie au cours des années. Une présentation des domaines d'applications est nécessaire pour une telle technologie. La renaissance de la maintenance intelligente et la rencontre de ce domaine avec la révolution industrielle 4.0 nous a poussé à chercher les techniques développées et les applications produites dans différentes perspectives. De plus, une introduction et une analyse des piliers de cette technologie est faite en partant de la plateforme de développement en arrivant à l'interface d'utilisateur. Cette phase est considérée comme une synthèse qui nous permet de mieux diriger nos explorations et nos expérimentations futures.

La seconde phase est l'exploration ayant pour but de proposer une approche d'implémentation de la réalité augmenté pour les opérations de maintenance à distance. Dans une première étape, pour bien introduire l'approche proposée, une présentation de la structure globale de l'approche a été introduite ainsi que les différents éléments (visuels et textuels) construisant notre vision de l'approche. Par la suite, pour mieux comprendre la structure particulière nous avons analysé les composants de l'Application et l'interaction entre ces composants pour introduire par la suite notre méthodologie d'implémentation. La première étape est de détailler l'Architecture du système, deuxièmement la description de l'interface d'utilisateur et la structure de communication ainsi que le logiciel de développement proposé. Ce travail est un guide d'implémentation d'une application de télémaintenance pour la mise en œuvre des interventions entre les experts de maintenance et les opérateurs du terrain.

La dernière phase du projet de recherche globale concentrera sur une autre perspective de maintenance 4.0. Il s'agit de l'étude et conception d'un environnement d'atelier de maintenance pour les interventions de maintenance sous le thème de formation dans le contexte d’un projet de forage hybride dans le secteur minier. Ce travail est reparti en trois étapes globales. La première est la description du contexte d’application et la méthodologie adoptée pour la mise en œuvre de l’environnement en associant la philosophie de conception des modèles 3D, les étapes de conception et l’adaptation à l’interface d’utilisateur. Deuxièmement, une présentation des outils utilisés pour notre environnement est faite incluant l’analyse du plan d’espace de l’atelier, les logiciels de conception et d’animation et finalement le déploiement de l’environnement virtuel. Pour compléter cette perspective nous avons ainsi proposé un appareil pour l’export d’environnement. Troisièmement, on parle de l’implémentation de l’environnement, en détaillant le scénario adopté et la démonstration des scènes et des cas.

6. ORGANISATION DU MEMOIRE :

Le premier chapitre du mémoire consiste à mieux comprendre le processus de maintenance intelligente ainsi la technologie de réalité augmenté. Ce chapitre présente les différents outils de maintenance intelligente aujourd’hui incluant l’intelligence artificielle, IoT, Big DATA, etc. et par la suite une description totale de la réalité augmentée. Ce chapitre présente ainsi les différentes méthodes existantes, les travaux et recherches antécédents réalisés dans ce domaine de la RA par différents chercheurs et les avancements trouvés par ces derniers. L’étude se présentera sous forme d’une revue de littérature permettant une meilleure compréhension du sujet et des lacunes rencontrés dans les travaux antérieures. Elle nous présentera aussi une ouverture d’horizon pour l’implémentation dans le cadre de l’industrie 4.0.

Le second chapitre aborde une approche d’instauration de la réalité augmenté pour les interventions de maintenance à distance. Ce travail détaillera l'architecture générale du système proposé en mettant l'accent sur la structure du cadre et les éléments d'exposition. À cet effet, on décrira dans cette vision les composants et les piliers ainsi que les différentes façons dont ces éléments interagissent les uns avec les autres. La dernière partie de ce chapitre se focalise sur le développement de l’approche en matière d'architecture et de l'interface graphique du cadre d'application. D’ailleurs, cette partie détaillera la structure de communication, les différents éléments composant le cadre d’interface et les scénarios d’intervention.

Le troisième chapitre s’agit d’une étude et conception d’un environnement d’atelier de maintenance pour le volet formatif des opérateurs de maintenance. Ce travail contient une description détaillée du contexte de la réalisation du projet en précisant la portée de la mise en œuvre ainsi que les objectifs visés. De plus, une description détaillée de la méthodologie proposée est présentée. En outre, nous avons présenté les outils utilisés pour créer l'environnement nécessaire à une mise en œuvre optimale de notre approche. Finalement, nous avons fait une présentation structurée de l'environnement que nous avons conçu, en précisant les scènes et les phases d'intervention.

La dernière partie du mémoire constitue une synthèse des approches et des conclusions adoptés dans les chapitres précédents. Elle propose une conclusion générale sur l’efficacité de la maintenance intelligente ainsi des deux technologies de RA et RV dans le processus de production. D’autre part, elle présente les avantages et les lacunes à surmonter délivrés par ces technologies. Cette partie ainsi ouvre les possibilités qui peuvent encore être explorées pour ces derniers.

CHAPITRE 1
L'UTILISATION DE LA REALITE AUGMENTEE DANS LES APPLICATIONS DE MAINTENANCE INDUSTRIELLE : PILIERS ET EXEMPLES.

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1.1 RESUME EN FRANÇAIS DU PREMIER ARTICLE

La réalité augmentée, en tant que technologie de pointe, a été intégrée principalement pour soutenir l'industrie manufacturière et en particulier la maintenance dans ses différentes perspectives. Cette technologie et son application font l'objet de recherches universitaires et académiques depuis une cinquantaine d'années. Au cours de la dernière décennie, la réalité augmentée a connu un développement visible qui a favorisé sa mise en œuvre dans l'industrie. Dans cet article, une chronologie de la technologie a été proposée en termes de travaux réalisés depuis le début de l'application de la réalité augmentée. En fait, certains problèmes ne facilitent pas l'intégration complète de la RA dans les applications industrielles en tant qu'outil d'ingénierie numérique. Cet article vise à démontrer l'état actuel de la RA dans le domaine de la maintenance et les limitations techniques les plus pertinentes. L'étude porte sur un grand nombre de travaux réalisés depuis 1997. Le document explore les perspectives et le développement des systèmes de RA en présentant le matériel, les logiciels et les solutions de mise en œuvre dans l'industrie manufacturière. Les conclusions de l'étude montrent quelques défauts et faiblesses de la technologie dans certains domaines. Une vision et des orientations utiles pour la technologie sont proposées, ainsi que des recommandations pour le matériel, le suivi, la surveillance et l'interaction.

Ce premier article, intitulé « *The use of Augmented reality in industrial maintenance applications: Pillars and examples.* », fut rédigé par son premier auteur Haitam Ichou. Le premier auteur a également écrit les parties concernant l'état de l'art et a fait les recherches nécessaires pour cette revue de littérature. Monsieur Noureddine Barka est à l'origine du projet de recherche et il a contribué à la suggestion de plusieurs axes de l'Article ainsi l'Amélioration de la rédaction pour la version finale.

1.2 TITRE DU PREMIER ARTICLE

The use of Augmented reality in industrial maintenance applications: Pillars and examples.

1.3 ABSTRACT

Augmented reality as an advanced technology has been integrated mainly to support the manufacturing industry and particularly maintenance in its different perspectives. This technology and its application have been a subject of university and academic research for about 50 years. During the last decade augmented reality has experienced a visible development, which has pushed its implementation in the industry. In this article, a chronology of the technology has been proposed in terms of the work done since the beginning of AR application. In fact, some problems do not facilitate the full integration of AR in industrial applications as a digital engineering tool. This paper aims to demonstrate the current state of AR in the maintenance scope and the most relevant technical limitations. The study includes a large number of works since 1997. The paper explores the prospects and development of AR systems by presenting hardware, software and implementation solutions in the manufacturing industry. As for conclusions, the study shows some flaws and weaknesses of the technology in some areas. A vision and useful directions for the technology are proposed as well as recommendations for the hardware, tracking, monitoring and interaction component.

1.4 NOMENCLATURE

AR	Augmented reality
XR	Extended reality
MR	Mixed reality
CPPS	Cyber-physical production systems
IoT	Internet of things
PDM	Predictive maintenance
CBM	Condition-based maintenance
TBM	Time-based maintenance
MTTF	Mean time to failure
MTTF	Mean time to failure
CCEB	Current condition evaluation-based
FCPB	Future condition prediction-based
FCPB	Future condition prediction-based
RUL	Remaining useful life
NDT	Non-destructive testing
CPS	Cyber-physical systems
IoS	Internet of systems
ML	Machine learning
DL	Deep learning

HMI	Human machine interface
AI	Artificial inteligence
HMD	Head mounted device
HHD	Handheld display
FOV	Field of view
SDK	System development kit
CAD	Computer aided design
SLAM	Simultaneous localization and mapping

1.5 INTRODUCTION

New technologies have a huge effect in industries nowadays. They have introduced a new era of manufacturing systems by adding new perspectives of quality, management and production. Digital technologies still central for a realization of intelligence in the manufacturing industry. Several pillars are recently deployed for a better efficiency in the ''Industry 4.0''. Real time connectivity, Data management and advanced devices integration give the rise for a new and creative manufacturing system. Leaded by Germany as the creator of the 4th generation industrial revolution (THE GERMAN ECONOMIC DEVELOPMENT AGENCY)[1] based in large part on the manufacturing and innovation of cyber-physical and systemic services. In principle, the industry 4.0 proposes a new industrial model (4.0) that is divided mainly in three big parts: a part of the components, the machines and the productive system. This new model ensures a connection that can take a real time property by the concretization of various technologies: it is a physical digital marriage. Such a combination is powered by the Internet of Things, blockchain, artificial intelligence and many other associated technologies. Among the development areas in which Industry 4.0 is interested is the cross-sectoral cooperation between production planning and maintenance. All this with the objective of guaranteeing the efficiency, speed and good quality of the maintenance service and subsequently implement a profitable production system [2]. The transition to Industry 4.0 means the application and implementation of new technologies and subsequently a profound change in manufacturing and human resources management [3].

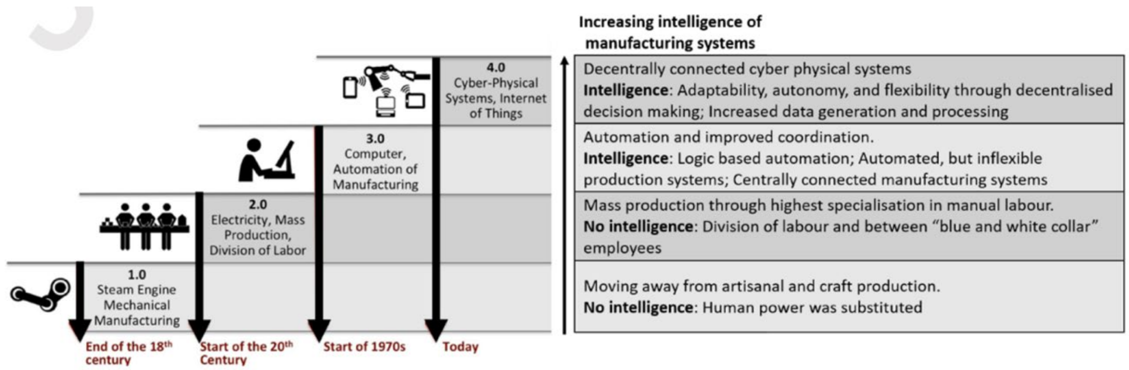

Figure 3: The four industrial revolutions [1]

In the context of Industry 4.0, to ensure a link and a bridge between the physical world and the virtual environment, new technologies are born. Here we speak of mixed reality, virtual reality and augmented reality. These three are grouped under the generic term of extended reality (Extended reality XR). Equipment maintenance is one of the main pillars of the manufacturing process. Augmented Reality (AR) applications supporting workers in complex service or maintenance tasks belong to the most desired industrial AR applications since the early days of AR research. Augmented reality has a remarkable role to play in the organization and performance of large amounts of usable CPPS data accessible in real time to users[4]. AR is therefore an indispensable core for realizing this human-centered industrial manufacturing 4.0 approach [5, 6] by supporting humans in an intelligent environment. The European Union has classified AR as a core technology that contributes to the development of smart factories. AR has had a focus of researchers to ensure and facilitate collaboration and interaction between operators and production systems[7].

Augmented reality is defined as a tool that enhances the real world using virtual objects[8]. On the other hand, AR systems have characteristics that make them unique in the intelligent industry. These characteristics can be summarized in five: 1- The combination of real and virtual objects within a virtual environment. 2-Interactive and real-time operation. 3- Geometric alignment of real and virtual objects in the same real environment [9]. AR has been used in many fields: entertainment, marketing, surgery, logistics, manufacturing, maintenance(...)[10, 11]. As far as maintenance is concerned, the use of such technology always shows academic benefits. By maintenance, we mean all the interventions that aim to restore, predict and predict all the functionalities of the product throughout its life cycle. In the case of industrial production equipment, we speak of industrial maintenance. The maintenance actions can take a technical form as well as administrative and managerial [12].

The studies of maintenance using augmented reality reveal more promising prospects especially in everything that concerns the development and improvement of human autonomous skills in making technical maintenance interventions, the management and planning of operations and the elaboration of a vision for effective decision making on the part of maintenance managers. The industry is starting to integrate AR technology little by little despite all the above. Its implementation in industry is starting to be beneficial although there are fewer examples. For this last reason, this article has. For this last reason, this article has for objective to create a base of works and a state of the art of the AR and to found a plan of analysis in terms of technicality used, material and applications while remaining in the perimeter of maintenance.

The format of this essay is as follows. In Section 2.6, a thorough analysis of the literature is done with a focus on technical maintenance and AR-related problems. The broad architecture of the proposed system is then detailed in Section 2.7, with a focus on the framework structure and the exposure elements. The remainder of Section 2.8 describes the components and pillars as well as the various ways in which these elements interact with one another. Finally, Section 2.9 develops the procedure, architecture, and GUI for our approach's application framework.

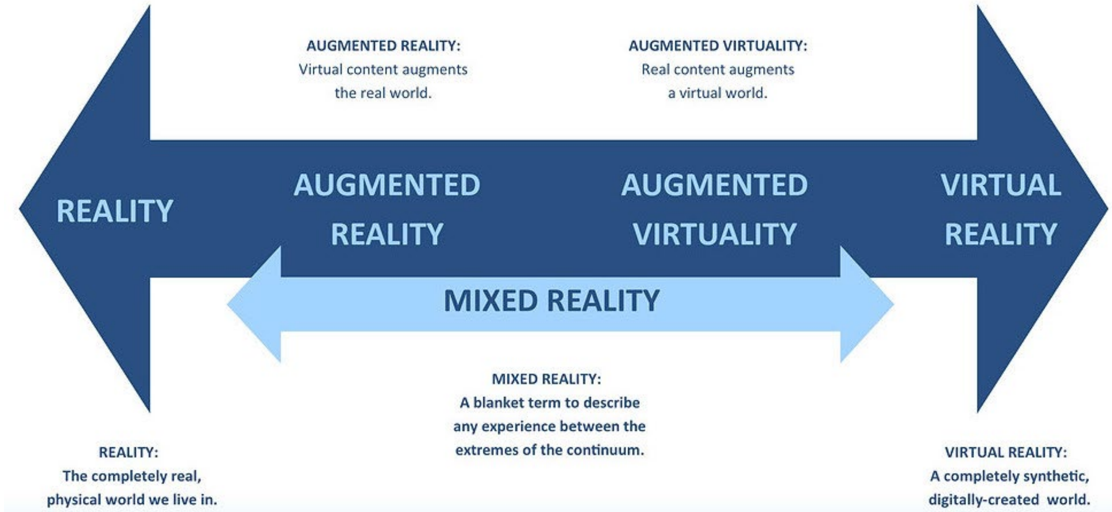

Figure 4: Reality-virtuality Continuum

1.6 SMART MAINTENANCE INDUSTRY 4.0

Smart manufacturing has been introduced in the era of Industry 4.0, the concept of advanced manufacturing. Such a concept is based on flexibility and adaptation. It is a system that adapts production lines to be flexible by adjusting the production processes of the unit for many products and in fluctuating conditions. All this with the aim of ensuring a combination of quality, productivity and flexibility and subsequently increase in order to achieve a personalized and sustainable product with an optimal management of resources [13, 14]. Industry 4.0 introduces the concept of the smart supply chain which implements an information exchange and integration of the supply chain. This is ensured by synchronizing production, on the one hand, and supplier management to avoid bullwhip effects by reducing delivery delays and anything that disrupts the information flow [15]. In the same context of Maintenance 4.0 and with the deployment of new connected technologies, all the above-mentioned tasks are performed by machines, which maximizes the useful life of equipment and machine components and subsequently avoid unplanned breakdowns. All this encompasses a machine health monitoring approach, these machines are made connected through IoT. This approach not only ensures maximum uptime but also saves money compared to preventive maintenance because interventions are only validated if their necessity is predicted.

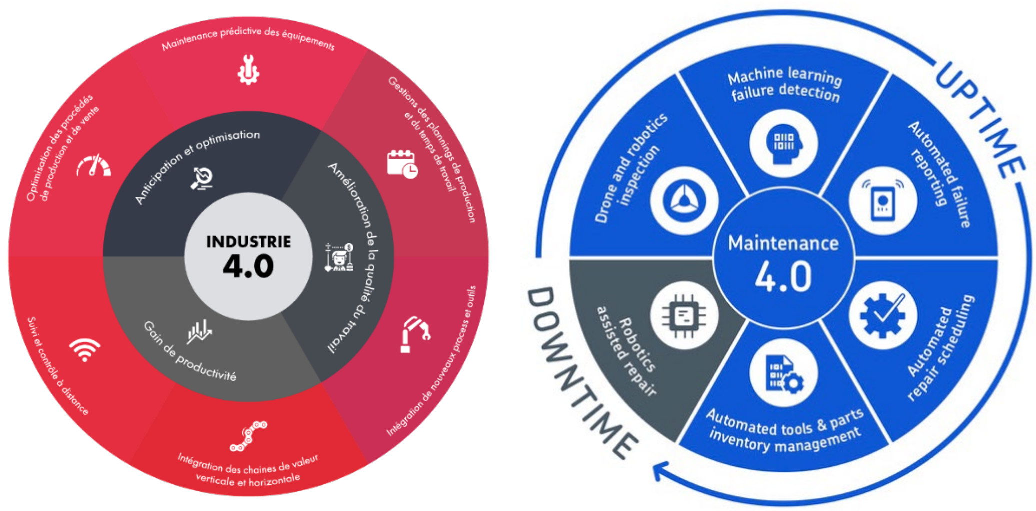

Figure 5: The concept of industry 4.0 and maintenance 4.0

1.6.1 Principle tools of smart maintenance

Recent innovations, such as cyber-physical systems (CPS), the Internet of Things (IoT), the Internet of Systems (IoS), Big Data, etc., have been adopted by industry 4.0 as central fundamentals of technological change within the framework of Industry 4.0 at the beginnings of the 21st century, during the fourth industrial revolution. Industries have adopted them for use in a variety of industrial frameworks, including maintenance, particularly predictive maintenance also known as maintenance 4.0.

1.6.1.1 Big DATA

Big data analytics has the ability to give feedback and extensive coordination within the context of Industry 4.0, both of which are essential for maximizing production efficiency. Sensors, actuators, network traffic, and log files are just a few examples of the sources and channels that can be mined for useful information that can be used for dynamic system reconfiguration and efficiency, as well as for performing direct management and control tasks

[120]. The development of smart analysis models and algorithms, made possible by the combination of Big Data Analytics and mining technology, contributes to the success of smart manufacturing. One of the more notable applications of Big Data is the digital twin concept that Industry 4.0 has introduced [121]. Another field that has benefited significantly from Big Data's application is manufacturing [5applsci], specifically manufacturing that is driven by Big Data and involves both predictive and proactive manufacturing.

Collecting, processing, and analyzing real-time Big Data from CPS is one of several anticipated phases necessary for the intelligent transformation of the maintenance function. Predictive maintenance relies heavily on this stage for failure prediction, intervention planning, and optimization. Human Machine Interfaces (HMIs) are commonly used by CPSs as their point of contact and interaction with humans [48]. CPPS (Cyber-Physical Production Systems) is a common term for referring to applications of this technology in industry, especially in the context of predictive maintenance or maintenance 4.0 [52], [53].

1.6.1.2 Cyber-Physical systems

Through the integration of computation, networking, and physical assets, cyber-physical systems (CPSs) intend to facilitate two-way communication between the digital and physical spheres [122]. Although the precise meaning of CPS might be debated, it is generally accepted that hardware (e.g., sensors, actuators, robots) and cyber software (communication, networking, and the internet) constitute the link between the physical world and the digital one. The efficacy of CPS in Industry 4.0 relies on the intelligent control of interconnected systems between its physical components and computational capabilities, making use of state-of-the-art technology in both domains [123]. Human Machine Interfaces (HMIs) facilitate the connection and communication between CPSs and humans [48]. CPPS (Cyber-Physical Production Systems) is a common term for referring to applications of this technology in industry, especially in the context of predictive maintenance or maintenance 4.0 [52], [53].

1.6.1.3 Internet of Things (IoT)/Industrial Internet of Things (IIoT)

IoT is considered as "A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [124]. The Internet of Things (IoT) refers to the infrastructure that enables various devices and/or assets to connect with one another. IoT is a word that has been widely used, and in each new context it adopts the name of its new domain of application. IoT-aided Robotics or Internet of Robotic Things (IoRT) is a novel concept that was introduced in Industrial Internet of Things (IIoT) [14], Internet of Service (IoS) [15], and Internet of Robotic Things (IoRT) [16]. These technologies came into existence as a result of the combination of Robotics and IoT. Sensors, actuators, and electronic software all have physical device embedding and are linked to multiple Internet networks in production systems. Sharing and exchanging data between manufacturing equipment, as well as between manufacturing devices and the service providers and customers of manufacturing devices, is made possible through the Internet of Things [17,18]. According to [49], the design of IoT systems is in the form of three layers (multi-layer system) namely IoT platform layer, IoT application layer, IoT industrial solutions layer. This design provides several advantages in terms of process efficiency and flexibility. In the industrial sector especially in the context of predictive maintenance or maintenance 4.0, the use of this technology is often known as IIoT (Industrial Internet of Things) [46], [47], [52], [55]. According to [55], in a survey of a set of manufacturing companies on the adoption of this technology as part of a predictive maintenance policy, almost 44% of companies are already applying it, and 27% are planning to use it in the near future.

1.6.1.4 Artificial intelligence

The switch to Industry 4.0 relies on artificial intelligence, a potent piece of technology capable of making possible the weaknesses of conventional approaches to industrial production. Increasing levels of connections, non-linearity, uncertainty, and data volume are all contributing factors to the growing complexity of modern industrial environments brought on by Industry 4.0 [125]. AI's development and the extensive adoption of ML (Machine Learning) and DL (Deep Learning) based approaches across industries have positioned these tools to play an essential part in the introduction of Industry 4.0 [126]. AI is one of the most important technologies for Industry 4.0 since it allows for the development, testing, and deployment of several machine learning algorithms for application in automated production settings [127]. Effects of AI-based approaches on Industry 4.0 include enhanced adaptability, productivity, and sustainability due to the autonomy of intelligent devices performing tasks like self-monitoring, interpretation, diagnosis, and analysis. With AI, it's possible to enhance the effectiveness and precision of prognosis for tasks like failure prediction and RUL estimation, maintenance intervention speed and quality, error rate reduction, maintenance plan planning and efficiency, profitability and optimization of resources and investments.

1.7 SMART MAINTENANCE AND AR TECHNOLOGY

AR technology has been around for the last five decades [56]. AR is an interesting product for consumers and industry more specifically. The relevant application of AR has become more powerful due to the progress developments in increasing computing power and miniaturization. AR systems display different data with a layer of information about the real environment, this has changed many perspectives to humans by giving more choices and options. This justifies the position of AR, according to the reality-virtuality continuum (fig2), it is located between the real and virtual environment which represent the extremes of the continuum [8]. Some researchers attribute the term AR only to applications whose content is 3D [9]. In this article we will quote the term AR in 2D and 3D applications. the AR system is mainly based on: 1- a sensor system 2- tracking system 3- processing unit 4- user interface.

1.7.1 Fields of application

AR is of great importance in our world today. Moreover, AR has been considered in several industrial scopes or environments. In this paper, the fields of application have been divided into six major industrial categories:

- Aeronautical industry;
- Mechanical maintenance;
- Consumer technology;
- Nuclear industry;
- Remote applications;

Different requirements are placed on the AR system and maintenance. AR as a system and its specifications are usually justified by the domain or field of application. Most of the related papers and works are taken by the mechanical maintenance and the plant maintenance fields.

1.7.1.1 Aviation industry

Several motivations justify the use of such technology in the aviation industry. First of all, there is the need to reduce the impact and risk of human error on maintenance operations, in order to improve air safety. There is also the view that with all the current developments, the application of traditional training methods has become impossible with the technology currently available on aircrafts [57]. AR support is very beneficial since today's complex systems and avionics require more demanding skills. The classic application steps of a maintenance intervention always lead to a difficulty of application with full reference to references, guides and manuals. The maintenance operator finds such a mission as a multi-task in terms of concentration, application and low-quality performance [58]. In the aviation industry, a minimum of 2000 hours is required for a maintenance inspector to train and this knowing that the skills and knowledge in such a field are not easily transferable from one maintainer to another [59]. The maintenance performance is essential in aviation for safe operation with minimum costs [60].

1.7.1.2 Mechanical maintenance

The mechanical field still the highest area of application. This field includes all the maintenance actions related to the mechanical part in different sectors of activity more particularly: automotive, railway and military. For the automotive industry a rate of 40% is that of maintenance and repair of the total costs of ownership of a vehicle during its entire life [61]. "The maintenance process is today an important aspect of competitiveness and profitability", is what Fiorentino [62] estimates in relation to the maintenance processes. [62] made a study of the application of AR and its effect on the profitability of such a system. He applied AR on an engine for a complex maintenance operation. The results were very impressive in terms of time improvement (up to 79%) and error rate reduction (up to 92.2%). Another interesting study is that of [63]. His problem is related to the railway industry, he tried to solve two problems of traditional maintenance in the same field:

- The transformation of guides and manuals into electronic multimedia;
- Providing a training device or tool for new technicians.

The problem of further delaying the overall maintenance process by using manuals has been the subject of several studies as well (e.g. [64, 65]). A total concentration is ensured by using HMDs instead of classical manuals, this was the subject of study of [66]. For a total optimization of the maintainer's movements, [67] states that: "reducing eye and head movements by improving spatial perception and thus increasing productivity". All this has been summarized by [68], he believes that implementing maintenance and return to instructions simultaneously wastes a lot of useful time. Moreover, all these concepts can be applicable for several fields of application.

1.7.1.3 Consumer technology

Consumer technology is a big part of our lives. The application of maintenance as a task in such a field has been the subject of several studies (e.g. printers, laptops...). The capabilities of the systems are furthermore shown in such a field of application. A first example is that of [69], when he demonstrated the role of AR in disassembly operations by doing the task of disassembling a computer fan. A frequently encountered example is that of [64], he sought to assemble and retrieve data on novice maintenance operators using AR and applying maintenance interventions on a laptop computer. The results of [64] showed the ultimate difference between AR and following paper-based instructions. Results that prove a reduction of errors and intervention time. Finally, the example of [70] is cited, which shows the application capabilities of AR for computer and printer maintenance operations. He also describes that both the automotive and aviation industries need more maintenance cost reduction. His paper describes a 40% reduction in travel and 30% reduction in maintenance costs.

1.7.1.4 Nuclear industry

Another interesting field of application for AR is nuclear power plants. Compared to other industries, a high degree of reliability is required in nuclear power plants. The application of several interventions is complex due to the working conditions. All this requires the production of numerous procedures which explains the cost and complexity of maintenance in nuclear power plants. It is necessary to ensure a minimum downtime of these plants with safety as an important parameter [71]. [72] presented several concepts in the same industry. He presented the important challenge of maintenance in the mining industry. Nakagawa stated that due to the tight and rigid schedule of the interventions required in the plants, the maintainers can make mistakes at any time resulting in extra time and costs. The power plants always present particular conditions and especially the presence of radioactive environments, that forces to think about an optimized maintenance [73]. Martinez in his paper cites the study of accessibility of the collimators of the LHC (Large Hadron Collider) and its changes after the design by installing new equipment.

1.7.1.5 Remote applications

The current trend in industry is to also design applications using AR for remote maintenance: Remote Maintenance. Remote maintenance is described as a collaboration between a maintenance operator and an expert who are in two completely different "physical" locations. It is also called "remote assistance" or "collaborative maintenance". So this article refers to several works [64, 69, 70, 74-80]. Traditional telephone support is still insufficient and cannot satisfy the complexity of current technology[78]. Wang mentioned that VR could be more effective for training perspective but AR could be more beneficial for real-time data and information transfer.[69, 81] indicate that AR for remote maintenance is 10% faster than traditional assistance. AR in relation to maintenance is relevant for applications in machine tool manufacturing. [70] states that cost is an important parameter for machine tool manufacturers, which is why manufacturers find it expansive to provide support to their customers. It should also be kept in mind that each machine is different from the other, hence the need to implement customized maintenance procedures. This vision can be beneficial in two ways: 1- Ensuring customer satisfaction, 2- Reducing maintenance costs. On its part, the automotive industry is a great field of application of remote collaboration. Nowadays, integrated sensors allow access to diagnostic and maintenance data[82, 83]. All actors related to the automotive industry could benefit from a new collaboration system, starting from car manufacturers to workshops and roadside assistance services. The definition of the product life cycle falls within the scope of remote AR. As an example, Wang [77] merged telepresence and AR technologies as a collaborative design system. Liverni [80] asserts that collaboration between maintenance operators and engineers on the same product by doing the same intervention in real time, face-to-face or remotely, could surely reduce the time to market of the product as well as ensure improved manufacturing quality.

Generally, for good profitability, product quality and accessibility these reasons are always mentioned: the constant need for improvement in terms of time, errors, safety and costs. These factors justify the use of AR technology. An investment in AR in a field of application changes depending on the needs and conditions of the applications.

1.7.2 Maintenance operations applications

Maintenance interventions in industry are done to ensure continuous improvement of components, minimize operating time and subsequently optimize the useful life of the component. In this article, we will mention the most known and common tasks and operations along the manufacturing line. These tasks are divided into four main categories: 1- Assembly and Disassembly, 2- Repair, 3- Diagnosis and 4- Training.

In scanning the related items, the training task component is the smallest area. Such a task is less solicited because the ultimate objective of AR is to reduce the need to apply a training phase in the process of integration of the maintenance intervention but in the other hand introduce this phase directly in the Application of the maintenance task. The objective is to propose a solution that directly affects the maintenance operation without the direct passage through the training [84-86]. AR ensures an immediate ability for the maintainer to do the task directly on the job[87].

1.7.2.1 Dis/Assembly

Among the maintenance tasks often done in industrial units, and based on the articles mentioned in this paper, assembly and disassembly seem to be the most common maintenance task. Azuma claimed in 1997 that real projection of 3D drawings in animation could be more effective in the assembly process than integration of traditional user manuals [88]. Westerfield recently considered AR to be "the ideal tool for situations that require the manipulation of objects, such as manual assembly"[10]. Yuan in his paper describes assembly as the most innovative and prospective application of augmented reality[68].

In the rest of this section several examples, taken from the literature, are presented for a full clarification of the use of AR for assembly tasks.

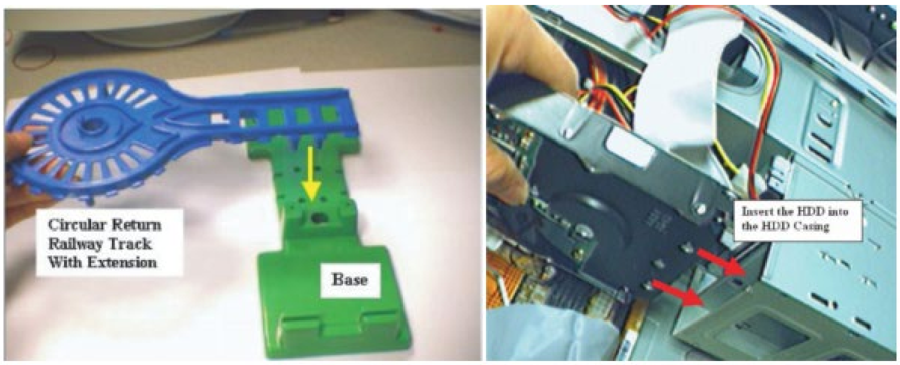

Figure 6: Example of assembly instruction on a train toy and a computer [69]

The first illustration shows a simple approach to implementing AR by overlaying virtual arrows and text on the real environment[60].

Figure 7: Step by step assembly [64]

The second example is illustrated from [64]. Its application is based on the integration of HHD to perform maintenance operations on consumer devices. Its application consists in displaying buttons to ensure a navigation in the procedure. Moreover, virtual animations are superimposed on the real environment for each step of the procedure.

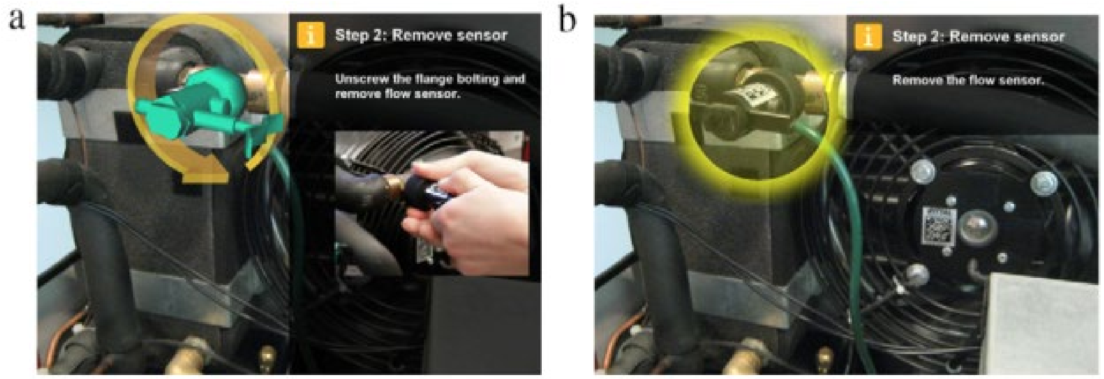

Figure 8: Two types of visualization for the same step in a disassembly procedure. (a):strong guidance-(b) :soft guidance [76]

Webel provides the third example [76]. It is a plan to show an effort to provide different levels of construction. According to him there are two main levels of guidance:

1. A strong level: It is a level that follows and supports the user in each step;
2. A soft level: This is a higher level with respect to the information provided, which is high level. It is dedicated to the most experienced users.

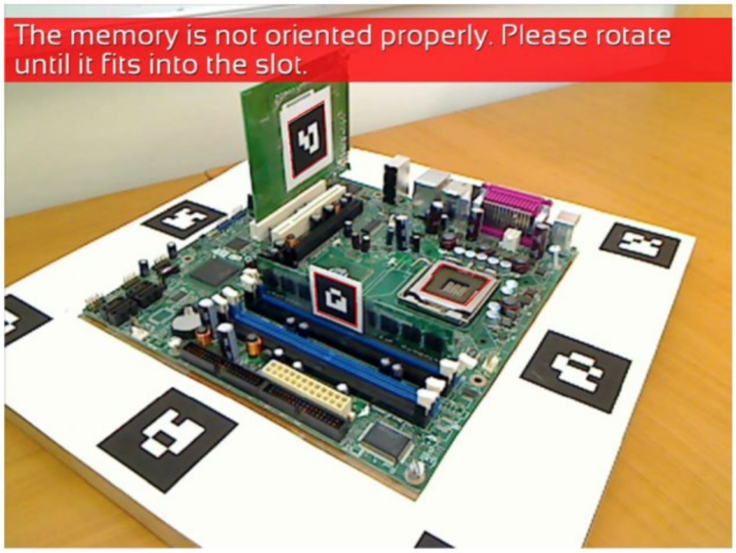

Figure 9: Negative feedback message in performance assembly through AR [10]

As for Westerfield [10], he integrated the real-time feedback of the operation into the AR process as shown in the figure. His application was able to show warning messages to guide and correct both the assembly procedure thanks to the position and orientation of the components.

Finally, Wang proposed a completely different approach. He targeted the first phase of component design by making the AR Application develop in such a way that it simulates the assembly procedure. He designed his study by taking into account several parameters that ensure optimal assembly. These parameters are mainly based on the rigidity of the shapes and contact surfaces between the real component and the virtual prototype. In his application he was able to show on the stage the forces that are calculated in real time.

All these examples give us a clear idea that even if the assembly as a procedure can be classified as a simple task, several types of training can appear that will help the operator throughout the application. A better AR solution should be achieved by considering all the requirements of each assembly procedure.

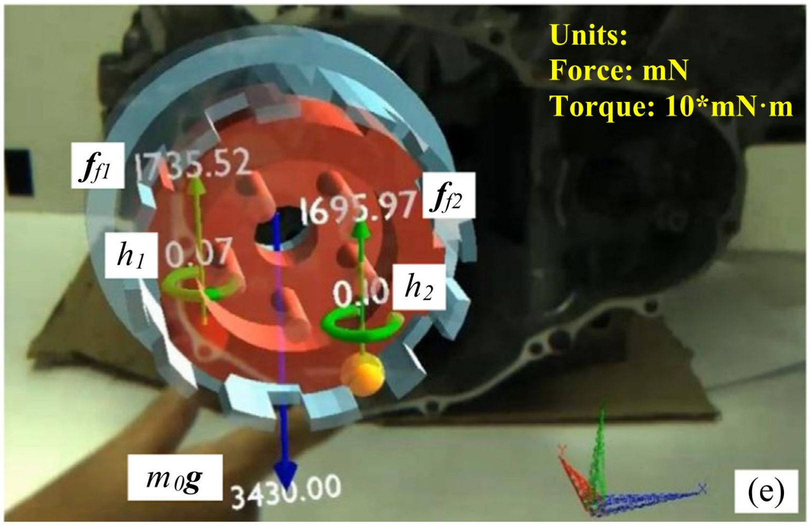

Figure 10: assembly planning throught AR [78]

1.7.2.2 Repair

Repair operations consist in restoring all functional properties of a device [89]. Generally, for such an operation, it is necessary to make a replacement or regeneration of the damaged or failed component.

1.7.2.3 Diagnosis

The inspection and diagnosis consist of two main actions: evaluation and analysis. These two tasks aim to evaluate the current state of the product and on the other hand analyze the causes of deterioration and functional degradation [90]. In most of the production lines today, there are sensors that provide data and information about the functionality and for a first preliminary diagnosis. AR can be beneficial in such tasks by displaying data or diagnostic results close to the object to be maintained [91].

1.7.2.4 Training

The training aims at transferring and passing on the expertise and maintenance skills to the maintainers [76]. The training can be accessible on site and offline, depending on the sector of activity. In the example of [92], he states that in the construction field often practical training is accepted. Wang combined information and human memory in the same field (construction) using AR. He superimposes several information and technical data on machines used in the construction domain (loaders, excavators, bulldozers...) to help operators complete tasks in the construction domain. On the other hand, [93] Neuman states that AR is a very effective way to retrieve information from memories. All this can demonstrate that AR has a very essential role in the training component and it has the same advantages as that of VR. AR has had such value in doing the execution in a real environment rather than an immersive environment [94].

1.8 AUGMENTED REALITY SYSTEM PILLARS

An AR application must go through a development process that ensures that the developer makes choices about the pillars of this application. These choices can be summarized in six main points:

1. The device to be used to expose the content to the real world;
2. The development platform;
3. The look and feel of the user interface;
4. The tracking technology;
5. The way of building the content.

1.8.1 Hardware

Analyzing the articles related to the subject, HMDs take a great place as hardware of AR applications. This article takes into consideration the work done since 1997. Numerous studies and attempts on the same subject have been made throughout the 90s but they are not taken into account. The devices mentioned throughout the study in this article are known devices available on the market. More and more applications are responding to the demands of customers and industries by addressing the two main factors: weight and resolution required. Indeed, the studies continue to be more demanding and are not limited to the classical criteria. For HMDs, there are two main types: 1- Transparent HMDs, 2- HMDs with video display[95, 96]. The first type is a combination of semi-transparent mirrors that reflect both the superimposed content and can show the actual content at the same time. In addition, they allow the reflection of user-generated content by computer. Two main optical architectures are used in this type of devices. They are the pupil formation and the non-pupil formation. The latter is often used in commercial HMDs. Kress [97] provides a paper in which he gives his detailed perspective of the optical approaches already mentioned (pupil formation and non-pupil formation). He concludes that: "there is no standard optical combiner architecture that prevails yet since a compromise must be found between a large eye box, a large field of view (FOV), the possibility of moving the image, etc.".

As for the second type of HMDs (the HMDs with video display), they superimpose the content and the information generated by the computer and they display them by a screen placed in front of the eye of the user [98, 99]. What specifies the HMDs with video display and the high gap of time between what happens in the real environment, the superimposed content and what is perceived by the eye. This is called latency. The latency of video display HMDs is higher than that of transparent HMDs because of the large amount of data to be processed. There are several factors that differentiate the use of one HMD from another. The challenges to be overcome by both types of HMDs mentioned are: system latency, resolution, field of view, scene distortion, viewpoint adaptation, ergonomics and cost [69, 91, 94, 100-102].

The HMDs provide a special experience when used for an AR application. They are portable and they give users the possibility to see the information generated by the computer superimposed on the real world directly in front of their eyes (8,46,63).

On the other hand, HHDs occupy the second place of the devices used in the works mentioned in this article. HHDs include consumer devices such as mobiles and tablets. What makes them two promising platforms for AR applications is their portability and capabilities

[95]. Kim in his paper [103] thinks that AR applications installed on smartphones have a great power to replace paper-based instructions in consumer cars. But on the other hand, the size of the device screen and the need for support make them not suitable for all maintenance interventions [104].

Other examples of devices used in AR applications are those installed in desktop PCs. This type of application has a high usage because this type of device is used for different purposes: remote maintenance management applications (on the engineer or expert side), for prototype development, to ensure the modification of AR procedures and for static maintenance activities (work bench). When used to perform the maintenance task, these types of applications often integrate cameras to capture the environment and operations.

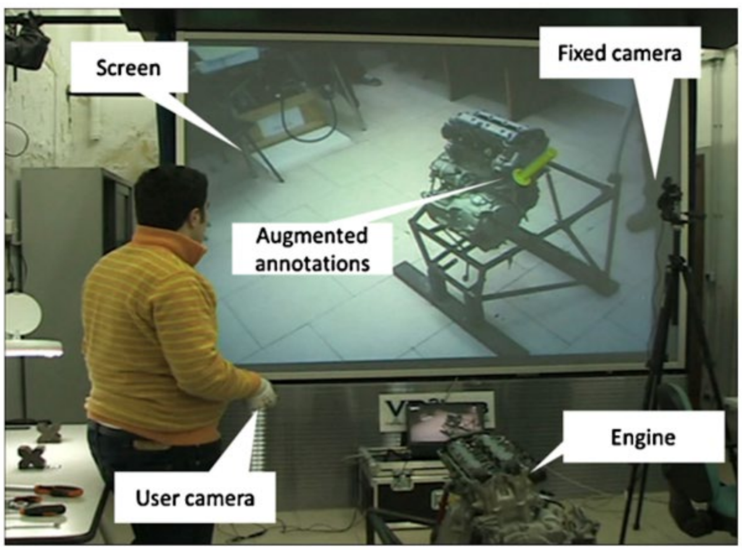

Figure 11: Interactive AR instructions on a large screen [62]

Some other applications with a smaller number of which other exploration and overlay systems are used. Fiorentino [62] in his article, mentions the use of a large screen to improve maintenance performance in a workshop environment. His system is mainly composed of three cameras: 1- a camera directed towards the object, 2- a camera directed towards the tooling and 3- a camera placed on the operator's body. In fact, in this case the system is called spatial AR [105] since the projection is done in real on the physical object. Finally, in the analyzed works we find haptic devices and other sensors. These devices are a means of collection used to gather more data about the operation and the environment. In [106], the interaction with virtual objects was improved with haptic devices. A vibrotactile wristband was used by Webel [76] to facilitate the execution of the task. The right direction is given to the operator thanks to the vibrations of the wristband. Other sensors can be used depending on the specific application.

Figure 12: Example of the utilization of a vibrotactile bracelet for supporting maintenance tasks [76]

1.8.2 Development platform

The selection of one or more platforms to be utilized for the development phase of an AR system is required during the process of developing the AR system. Medium-level and low-level programming languages are utilized frequently for augmented reality applications within the field of maintenance. When referring to a programming language, the terms "medium level" and "low level" indicate that it is more similar to human language than it is to machine language. In the works that are being examined in this article, the development process is not always completely specified. Because of this, the most popular programming languages haven't been highlighted or listed anywhere. C++, C#, Java, HTML, CSS, Python, Visual Basic, and PHP are the languages that are utilized the most frequently in the majority of application contexts. OpenCV (Open-source computer vision), OpenGL (for generating 3D and 2D graphics), and MATLAB libraries are only a few of the many used throughout development.

Figure 13: Example of animation related with aviation industry [57]

On the other hand, such languages require highly skilled people to develop such systems. The use of SDKs (system development kits) is becoming more and more common in recent times as they follow the trends in the field as well as generally accompany new devices on the market (HMD, HHD...). In most cases for the development of an AR application, SDKs must be included in a game engine or software with a medium/low level programming language. There are several game engines for application development but the most commonly used are Unity3D and Unreal. These user-friendly platforms make it possible to create applications regardless of the level of knowledge of programming languages. However, they require experienced AR personnel. Finally, several other platforms were mentioned in the articles reviewed. As for the creation of 3D content, it is provided by 3D modeling platforms such as: Rhinoceros, Solidworks, Catia and 3dsMAX.

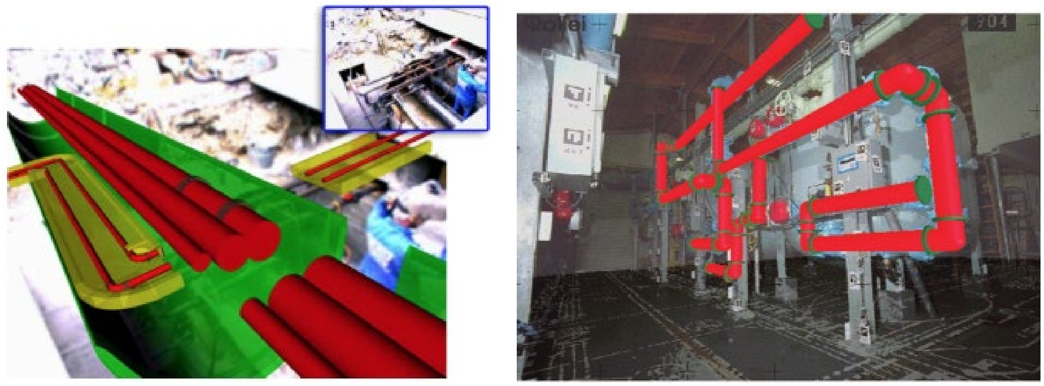

Figure 14: Examples of 3D static superimposition on the real environment for underground infrastructure [94]

1.8.3 Tracking

According to Siltanen [107], tracking is the most important component of augmented reality systems because of the function it plays in calculating the relative position of the camera in relation to the supervised object in real time. The term "pose" refers to both the location and the orientation of the camera in relation to the object. Another element has been mentioned by Ong [100], who affirms that precise tracing needs to be performed in order to find both the users and their movements in the environment. This was mentioned as a factor that must be taken into consideration. This is an absolute must for any augmented reality application. [96] Tracking has emerged as one of the most important research areas in AR. Visual or sensor-based tracking can both be used. We talk about a hybrid tracking when both of these approaches are employed together [108].

The "a priori" approach and the "had-oc" method are the two primary classifications that can be applied to visual tracking. The first one indicates that the system is already "a priori" aware of the target object that it will be tracking. They are able to be categorized as model-based, feature-based, and marker-based, respectively. This indicates that the a-priori information that is accessible consists of a model, a feature map, and a marker in that order. On the other hand, the information may be generated through the use of a had-oc visual tracking method, which would then serve as the basis for the initialization of the a-priori visual tracking method [107]. The following figure is a schematic representation of the tracking strategies that were mentioned earlier.

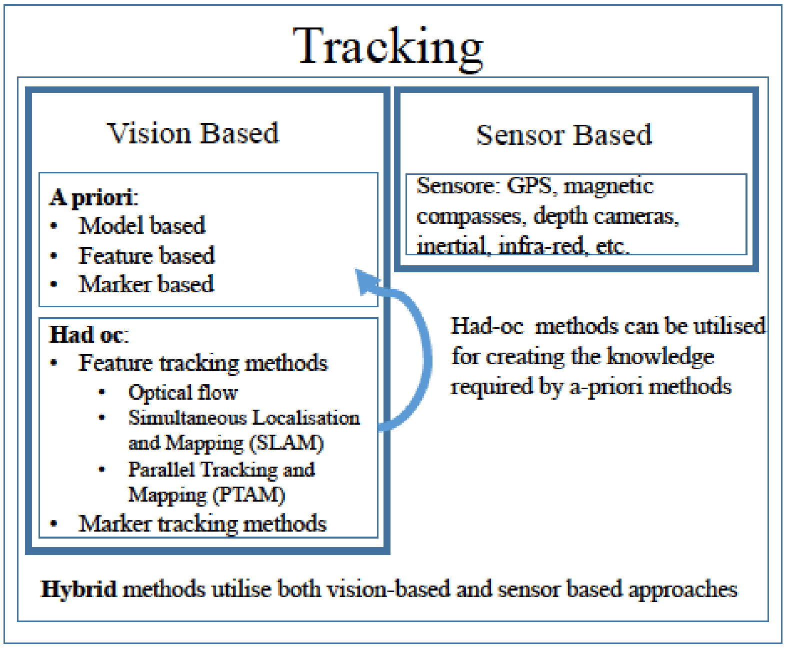

Figure 15: Scheme of the tracking approaches [59]

There is a big difference between recognition and tracking. Recognition does not depend on any prior information provided by the camera and aims at estimating the camera pose. Recognition is implemented at the initiation of the AR system and for each tracking failure. As for tracking, it aims at following the camera pose based on the previous image from the camera [109].

90% of the papers treated in this work used vision-based tracking. Vision-based methods are generally preferred due to the wide availability of RGB cameras on different hardware used for AR. The information required to perform "a-priori" tracking is usually developed by the authors for their project needs.

Sana [64] in his study made a combination of both an "a-priori" model and an "a-priori" feature (by images). The former is more robust and reliable because it does not depend on different environmental conditions such as lighting and materials (etc...). The limitation lies in the availability of CAD models. Platonov [102] in turn states that CAD-based tracking can solve several problems such as partial occlusions and fast movements.

In an industrial environment, the marker approach (which is previously considered robust and accurate) may not be effective [62]. Marker-based tracking consists of placing physical markers on the component or equipment to be maintained. A precise and correct design is required for the markers for a good configuration. Several parameters are registered a-priori for the RA system for the markers, here we mention especially their position and orientation on the real component to be maintained. From this logic, recognizing the marker is the same as recognizing the object. The limitation of marker-based tracking is the total or partial visibility of the markers, a condition that will not be valid if they are not in the visual field of the camera. In an industrial environment, several obstacles can mask and disturb the visuality of the markers partially or totally (work personnel, machines, tools etc...). This can lead to a failure of the AR system [80]. Another condition for a correct operation is the maintenance of the markers so that they remain clean and undamaged. For all these reasons, marker-based tracking is not always effective in industrial environments with harsh conditions [75]. For example, the aerospace industry does not consider marker-based tracking to be effective in its AR applications, so it will be unacceptable to apply markers in the Real Environment [57]. To solve this problem De Crescenzio [57] and Koch [110] propose the application of natural markers. Their solution lies on the use of fudicial images already existing in the application environment, to this effect it will not be necessary to place markers in the facilities. On the other hand, in the field of construction, for example, the hybrid tracking technology is well considered. In such a field, AR systems take advantage of GPS for an improvement of the tracking accuracy [111].

1.8.4 Visualization

The dynamic 2D/3D method is the most commonly used method. This method is more powerful than other methods since it gives more vivid instructions to maintainers and operators by implementing 2D and 3D animations [77]. It is more effective for unskilled operators [57]. These superimposed animations show the task in the correct and optimal way that the operator can perform the task. All these instructions are more effective than instructions displayed on paper [62].

Figure 16: Examples of natural markers [110]

Static 2D/3D models are another effective way to overlay information. Indeed, in some situations, it is not essential to give animations for maintenance tasks, however, a static model containing relevant information to perform, for example, inspections or other operations.

Schall in his study [112], he proposes to superimpose a 3D model of infrastructure below ground on a construction site (FIGURE 13). Navab [94] in turn in his study, presents a promising application for the overlay and visualization of 3D models in industrial environments.

Text thus is another but less intrusive way to provide machine-related information to an Assembly task. An advantage of textual content is its ability to be updated easily so it is a less complicated creation and modification advantage. In addition, textual content and its overlay does not obstruct the field of view. Textual information is an effective way to improve maintenance performance for already qualified maintainers.

Audio guidance does not have much presence in AR applications to support maintenance and repair operations. This small percentage of audio guidance, should not be confused with the different voice recognition systems to navigate in AR systems. Generally, it is necessary to mention that to develop the best AR application in terms of efficiency and flexibility, content and context requirements must be taken into account. In his paper, Engeleke [113], believes that it is up to the operators to decide the right form that best suits them to visualize the content. In his research, he proposes the possibility of diversifying the way of overlaying and switching from one visualization method to another in a flexible way. The system that needs to be maintained is superimposed on the actual environment, as seen on the left. The comprehensive CAD model of the assembly can be seen in the centre of the image. On the right, AR draws attention to the region of the 2D illustration that is relevant to the maintenance operation. Manual instructions can be found at the bottom of the page. (Figure 17).

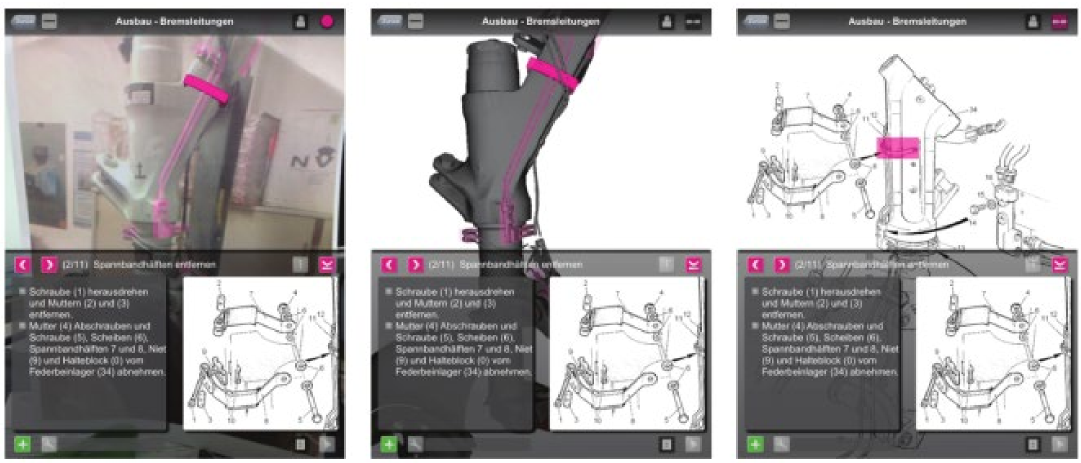

Figure 17: Three visualization method proposed by Engelke [113]

1.8.5 Authoring solution

The term "authoring system" refers to the process of creating digital content that is intended to augment reality [114].

Santos [115] in his study, he mentions the "authoring tools" as one of the main problems related to AR content without forgetting the design of the instruction and the content management tools. According to Langlotz [116], authoring tools are AR's effective solution to the widely known content problem. Bae [117] in turn confirms that these tools are one of the two key components of AR along with the correct estimation of the pose.

There are four main categories of the "authoring system". The first one includes the processes of manual creation that with which the content is generated manually.

This category includes not only the creation of the different 2D/3D static/dynamic models, but also the implementation in the AR system: localization, orientation etc. (...) On the other hand, the manual creation remains expensive due to the time and skills invested for its execution. The professional skills involved are [114]:

1. Programming;
2. Modeling;
3. Animation.

In order to provide an optimal and more practical solution for the creation problem, several studies develop different creation methodologies. In this paper, the methodologies mentioned are: Annotations, boxes and automation.

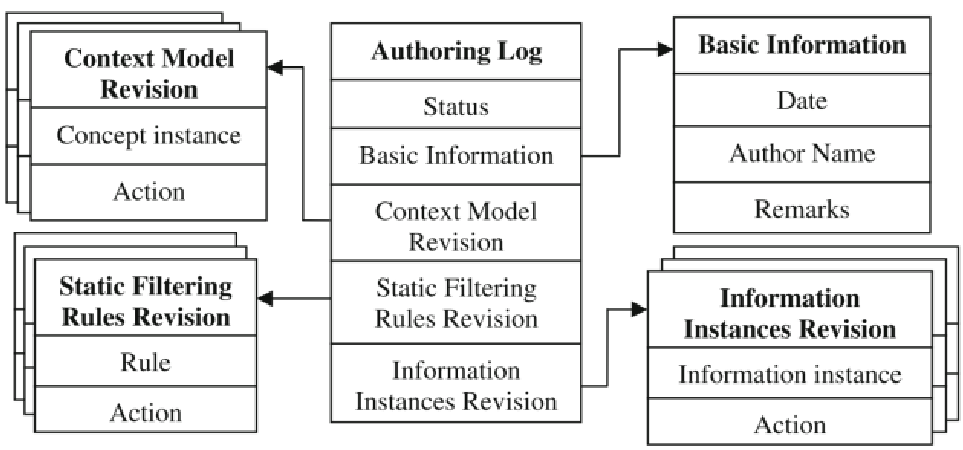

Figure 18: Technicians authoring log proposed by Zhu [75]

The first approach, which has been discussed before, involves the addition of virtual elements to a realistic environment. Klinker [71] defines those annotations as a set of basic maintenance operations. These tasks include highlighting, labelling, presenting text informations, removing details, updating exposed elements, establishing a compass, to hide and display information, and removing content. It is crucial to emphasize the fact that both static and dynamic material in 3D cannot be produced by the use of annotations. Alvarez [109] suggests in his research that they can be replaced by manually linking elements to an image, and he has made use of SLAM techniques in order to ensure that the environment is correctly registered. In his own right, Jung [118] designed an annotation system that was connected to the web. To facilitate better cooperation among designers, he developed a web-based annotation system that allows notes to be attached to 3D models. Nee [106] highlights applications that are comparable to this one and brings up the point that annotations attempt to facilitate the exchange of choices regarding design in a collaborative system.

The second approach is designed to construct AR operations (task-by-task procedures) without requiring an in-depth understanding of programming techniques for computers. It is vital to explain the concept that Havard [69] employed in order to make the application of this strategy easier to understand. Through his study, he developed a model of the maintenance procedures for AR by specifying entity, external entity, actions, maintenance and operation. He states entity as the smallest and the most insignificant component of the system that needs to be maintained (Same thing for the external entity). He defines actions as the activities to be performed, maintenance as series of actions and operation as a list of maintenance operations.

1.9 AR TECHNOLOGY: VISION AND FUTURE PERSPECTIVES

In the different academic cycles, research on AR systems has proven to be very important. But on the other hand, there is a need for further improvements that are necessary to have a more robust, reliable and flexible solution for practical implementation [70, 96, 100, 107]. As discussed throughout this paper, the main research topics in terms of design and insturatation of an AR system are the following:

1. Hardware: devices used for AR;
2. Recognition/Tracking: in terms of algorithms;

3. User-AR interaction;
4. Authoring solution;
5. Communication management tool;
6. Visualization and ergonomics.

These solutions and recommendations for future work are described in the following section.

1.9.1 Hardware future

Each device discussed in section 5.1 has advantages and disadvantages. Concerning the HMD, they prove their places because of their mobility and their ability to superimpose the content and the computer-generated information in front of the eye. But in the other side, this device remains uncomfortable, it has a limited field of vision and moreover it can distort the 3D images [96]. Several consequences are directly related to the point of view. This visibility affects the complete and effective application and the safety of the operations, the degradation of the virtual content in low quality and the distortion which can cause diseases. As for HHDs, they require a physical support system that does not affect operations, even if they are portable. Thus, the dimensions of their screen only allow to superimpose a limited amount of information and content. Indeed, for the other devices mentioned, their mobility remains null and their applications will not be integrated in all the maintenance operations performed by the operators [65]. The devices available on the market that support AR systems nowadays have some shortcomings in their capabilities and performances. Here we are talking especially about energy consumption, processing power, telecommunications, memory and resolution of the cameras must be improved [107]. For this reason, future AR hardware will see a strong implementation of sensors and haptic devices. The first improvement will ensure a greater capacity of AR by finding a solution to current problems. The second enhancement will strengthen mixed reality technology by providing tangible feedback to users of AR systems. In the near future, we should see a stronger integration of virtual retinal displays and AR contact lenses [107] as well as 3D hologram projectors.

1.9.2 Tracking' future

Different environmental conditions such as illumination, occlusion and materials (etc…) affect vision-based techniques. As for lighting, it has been partially solved by histogram equalization. But on the other hand, the accumulation of errors due to this illumination makes the tracking weak and not very robust [102]. Future solutions tend to overcome this illumination problem by using CAD models to extract the features (edges) of the virtual object and then make a comparison with the real object. Captured by the camera. However, this type of process can only be applied for an initiation stage of AR systems. After the object recognition, the tracking must be based on the object initially captured by the camera (RGB or other).

Some tracking techniques may be more robust than others, in specific applications. However, their reliability is not always considered adequate for the industrial environment [85, 96, 100].

1.9.3 Interaction between the user and the AR

Finally, an improvement of the user-AR interaction has to be taken into consideration. Today, we can talk about several skills required for an efficient development and maintenance of an AR system (programming, design and modeling, animation and experience and information standardization etc.). On the other hand, the fragmentation of the development platform remains a problem for the developers of AR systems [107, 119]. A very essential parameter acts on the efficiency and flexibility of an AR system. It is to make the AR system easy to maintain and to update. For this purpose new authoring solutions and content management tools have to be implemented [113]. The reconfigurability of the future AR system is essential, hence the need to improve the flexibility of authoring tools [70]. Moreover, the need to understand the best way to visualize the information depending on the operation and the environment must be taken into consideration. Ordinary visualization and vision-haptic visualization must be explored [115]. Thus, the way in which information is brought to the operators and maintainers needs to be studied. Future trends include the use of the haptic modality to transfer knowledge to the operator [76].

Adaptability is a requirement for future AR systems. They need to be able to collect data from any kind of maintenance procedure as well as frequently record the user's intentions when they are carrying out a maintenance task. It is possible that the information that was collected will be utilized to improve both the process of providing training or the procedure of maintenance itself [76].

1.10 CONCLUSION

This article offers a comprehensive look at the research done on augmented reality systems and their value to the manufacturing sector. This review demonstrates various approaches to augmented reality systems within the context of industry 4.0 particularly for maintenance operations, each with its own set of criteria oriented toward particular fields and tasks. In answering the first question, we explored the primary obstacles to using AR in maintenance. Articles and concentrates on future AR research directions and fields have been provided, offering a response to the second question. In general, augmented reality technology lacks the level of maturity required to meet the rigorous reliability and robustness standards demanded by the manufacturing sector. More Effective HMDs are needed, as are tools for creating AR content and enhancing tracking's reliability.

The goal of future research could be to systematically investigate the connections between AR systems and their implementation. Generally, no universal framework or set of guidelines for implementing AR in maintenance has been identified. Furthermore, in the broader context of digital engineering, a major question arises: the effective role of AR in relation to VR and MR. An application of the experience accumulated in introducing VR can be exploited to accelerate the implementation of AR.

However, as mentioned by this study, there are a number of areas requiring more development. AR is getting very near to being able to deploy its full potential.

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CHAPITRE 2
APPROCHE PROPOSEE POUR LA MISE EN ŒUVRE DE LA REALITE AUGMENTEE POUR LES OPERATIONS DE MAINTENANCE A DISTANCE DANS L'INDUSTRIE MANUFACTURIERE.

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2.1. RESUME EN FRANÇAIS DU DEUXIEME ARTICLE

Aider les opérateurs de maintenance avec des applications de réalité augmentée (RA) a toujours été un cas d'utilisation clé pour prouver l'avantage de la RA. Cependant, ces applications de RA ne sont pas encore populaires dans l'industrie manufacturière, ce qui peut s'expliquer par les exigences complexes de ce secteur. La RA est particulièrement utile dans l'environnement de fabrication où un ensemble diversifié de processus, tels que l'assemblage et la maintenance, doit être exécuté de la manière la plus rentable et la plus efficace possible. En outre, l'informatique en nuage a permis de fournir des solutions de haute qualité, ce qui est particulièrement important dans le contexte de la maintenance. Cependant, comme les machines modernes deviennent de plus en plus complexes, la maintenance doit être effectuée par un personnel à la fois expert et bien formé. En outre, l'assistance prend du temps et est coûteuse sur le plan financier. Bien que la réalité augmentée (RA) soit une technologie essentielle qui permet de construire des outils d'assistance à la maintenance fiable, ces outils sont limités à la fourniture de scénarios prédéterminés et ne peuvent couvrir qu'un nombre limité de scénarios possibles. Ce travail de recherche propose une approche de mise en œuvre d'un système de maintenance en temps réel basé sur la réalité augmentée pour l'industrie manufacturière. Il propose un cadre de méthodes appropriées permettant aux techniciens

d'atelier de communiquer avec les ingénieurs professionnels en utilisant un retour d'information immédiat au niveau de l'opérateur.

Ce deuxième article, intitulé « *Proposed approach to the implementation of augmented reality for maintenance operations in the manufacturing industry.* », fut essentiellement rédigé par son premier auteur Haitam Ichou qui a également réalisé toutes les conceptions et les plans discutés. Le premier auteur a également écrit les parties concernant l'état de l'art et a fait l'analyse des architectures proposées. Monsieur Noureddine Barka est le deuxième auteur de cet article. Il est à l'origine du projet de recherche proposant l'approche et ces objectifs ainsi il a contribué à l'amélioration de la rédaction pour la version finale.

2.2. TITRE DU DEUXIEME ARTICLE

Proposed approach to the implementation of augmented reality for maintenance operations in the manufacturing industry.

2.3. ABSTRACT

Assisting maintenance workers with augmented reality (AR) applications has always been a key use-case to prove the advantage of AR. However, these AR applications are not yet popular in the manufacturing industry, which may be due to the complex requirements of the industry. AR is especially useful in the manufacturing environment where a diverse set of processes, such as assembly and maintenance, must be performed in the most cost-effective and efficient method possible. In addition, Cloud Computing has made it possible to provide solutions of a high quality, which is particularly important in the context of maintenance. However, because modern machinery becomes more complex, maintenance must be performed by personnel who are both expert and well-trained. Additionally, support is both time consuming and expensive financially. Even though augmented reality (AR) is an essential technology that makes it possible to construct dependable maintenance assistance tools, these tools are restricted to the provision of predetermined scenarios and can

only cover a limited number of possible scenarios. This research work provides an implementation approach for an AR real-time maintenance system for manufacturing industry. A framework of appropriate methods for shop-floor technicians to communicate with professional engineers using operator-level feedback that is immediate is proposed.

2.4. NOMENCLATURE

PLM	Product life management
MRO	Maintenance, repair and operations
KPI	Key performance indicators
PSS	Product service system
IM	Information mappinng
STE	Simplified technical english
CNL	Controleled natural language
DITA	Darwin information typing architecture
XML	Extensible markup language
GUI	General user interface
SME	Small and midsize entreprise
DG	Design guidelines
SQL	Structured query language
API	Application programming interface

2.5. INTRODUCTION

A very particular advantage for AR is its possibility of integration in any stage of the production chain and in every stage of PLM. Several applications illustrate the use of AR and its flexibility [1] gives us the Example of integration of AR in the process of development of facilities by visualizing the floor plan by implementing an interactive environment for the developer. Starting from product design and arriving at all stages of manufacturing AR can be a simulation tool that can enhance product development [2]. On a manufacturing process AR can be used in various applications. Assembly [3], Quality Assurance [4], Collaboration and Safety [5] are all concrete examples for this effective use. Moving beyond the manufacturing stage and eventually to consumption, the product can be viewed, tried and analyzed by consumers. Thus, this product can be an integral part in the daily life of the consumer even before the actual use [6]. AR can be used as a diagnostic tool for the product in case of damage and for easy troubleshooting in case of problems [7]. Finally, at the end of the product's life cycle, AR can be used as a disassembly tool and help in recycling spare parts and recovering materials [8][9]. AR on the other hand, can be a decision support tool and an effective way to reduce costs and increase efficiency throughout the manufacturing stage of PLM. AR is a tool that can combine several advantages in relation to the behavior and state of the operator. Here, we are talking about a tool that reduces the cognitive load of The format of this essay is as follows. In Section 2.6, a thorough analysis of the literature is done with a focus on technical maintenance and AR-related problems. The broad architecture of the proposed system is then detailed in Section 2.7, with a focus on the framework structure and the exposure elements. The remainder of Section 2.8 describes the components and pillars as well as the various ways in which these elements interact with one another. Finally, Section 2.9 develops the procedure, architecture, and GUI for our approach's application framework.

the user by giving the right information at the right time without disrupting his concentration [10] subsequently allowing the industry to achieve its objectives. The objective of this paper is to propose an application approach to implement an augmented reality system at the intersection of AR, manufacturing and artificial intelligence (AI).

Noise is among the most complex parameters in a manufacturing environment, so it is not practical and obvious to include audio and voice elements in AR-assisted manufacturing applications without thinking about an alternative method of interaction with the user using rigorous noise reduction methods [11].

Thus, due to the obligation, in the majority of situations, to wear personal protective equipment, the operator faces a limitation of other modalities such as haptics. For this reason, this work focuses on the concretization of an approach that will converge the maximum of the modalities including the visual one. To be more precise, we will focus on the description of a system that will increase the capacity of the operator to organize himself in front of the maintenance operations by creating a remote information flow with the entity responsible for the maintenance interventions. Therefore, we intend to replace all the paper data received in real time including the use of audio, video and graphic files or other sensory data as input data due to some miniature ergonomic devices such as mobiles, for example, which can be equipped with both a camera and a screen to respectively acquire data and broadcast the enhanced content.

The format of this essay is as follows. In Section 2.6, a thorough analysis of the literature is done with a focus on technical maintenance and AR-related problems. The broad architecture of the proposed system is then detailed in Section 2.7, with a focus on the framework structure and the exposure elements. The remainder of Section 2.8 describes the components and pillars as well as the various ways in which these elements interact with one another. Finally, Section 2.9 develops the procedure, architecture, and GUI for our approach's application framework.

2.6. LITERATURE REVIEW

The following literature review is made based on the research methodology adopted in the article [12] for a thorough and well-structured analysis adapting to the constraints of the present research work. All the bibliographic base (30 articles) of research has been well followed and examined mainly according to the year of publication for a clear chronology of the works, starting from the articles dating from more than a decade and arriving to the works published recently. This chronology, presents an evolution of AR over the past years and then concludes on the current trends of AR in the maintenance field. To generate the research database, several scientific article search platforms were used: Scopus, Google Scholar, ResearchGate, ScienceDirect and Web of Science.

2.6.1. Augmented reality as part of the modern manufacturing system

The maintenance as a set of complex processes, is a fundamental element of the production chain while ensuring a longer duration of the physical asset's lifetimes subsequently their continuous and failure-free operations. All this justifies the important number of works analyzing this core of the production units that aim to describe and analyze its aspects. Each state of the assets of a production unit is associated with a maintenance activity. Indeed, all these maintenance activities are classified into several types. The most common types are:

- Corrective maintenance;
- Preventive maintenance;
- Risk-based maintenance;
- Condition-based maintenance [13];

Following the trend and for an adaptation to the different challenges posed by the current industry, several modes and policies of maintenance are developed in order to satisfy all these industrial needs. In spite of all these efforts, companies are not yet able to develop an optimal policy for a good equipment maintenance plan. All this changes according to the model, the vision and especially the objectives set by the company. However, all the policies and different maintenance plans have a unique importance for the researchers who develop them more than the industries. In this vision, this paper will describe a convergence of several policies in order to assist and enhance the user (maintenance operator) in several operations including especially corrective operations (in case of unplanned shutdowns or inadequate standard operating procedures). Moreover, this article is a development of the classical or corrective maintenance with improvements for an efficient guidance of the maintainers.

Maintenance has undergone several improvements during the last decade. This modernization of maintenance by introducing several features such as digitalization and decentralization. The decentralization has a big place in industries nowadays. This is called the decentralization of manufacturing networks. In many situations, industries are faced with the separation of manufacturing and production units on the one hand and company headquarters on the other. This constraint forces the assurance of a means to make the communication between the two entities less difficult [14], [15]. There are three main functionalities to be established for manufacturing systems: monitoring and control, operation and remote maintenance [16], [17].

2.6.2. Maintenance in industry 4.0

The manufacturing industry has been undergoing a remarkable evolution in recent years in relation to the digitization and digitalization of systems within the framework of Industry 4.0. In parallel with this current technological revolution, maintenance (like many other areas directly related to the manufacturing perimeter) has been able to improve thanks to all the advances in digital technologies. The support on the use of data or Big DATA analysis has become the core of maintenance today. The integration of the technologies already mentioned have helped to establish this core. For example, the IoT is considered the main factor for the emergence of the principle of Industry 4.0 (intelligent industry) and as the basic technology of cyber-physical systems.

Starting with inventory, Industry 4.0 established new policies to properly manage components and spare parts. Industry 4.0 has been able to build an MRO classification according to the uses of each category. Additive manufacturing collaborates with this policy by facilitating the reduction of production time for components and spare parts [18]–[25].

The introduction of Industry 4.0 has as its main objective, for all applications, the assurance of a maximum production time for the production chain and thus the increase of productivity and the optimal reduction of production costs.

In the context of the ongoing work on data analysis and Big Data analysis, several researchers have been able to identify the strengths and weaknesses of Big Data. [26] describes an approach illustrates the use cases of Big DATA in the context of industry 4.0 and its application in the different production chains. This integration is progressively taking place within the development, marketing and distribution chains. Among the most interesting examples we find [26], which studies in its paper the implementation of a predictive maintenance system. The subject of study is mainly on stainless steel, where the author processes and analyzes data from the machines of the steel sheet production process. Predictive maintenance is effectively introduced in Industry 4.0 through the use of algorithms giving the status of assets in real time by making a prediction of different future failures. It can be said that it is an essential decision support tool. As already mentioned, decision algorithms are a very essential tool in the context of predictive maintenance [27], [28]. [29] describes the role of predictive maintenance as an advanced platform for production systems by acting on its methods and maintenance tools.

The implementation of a flexible maintenance system remains a challenge for any production line. For a new maintenance system several obstacles can be in place. Generally, this situation refers in most cases to the experience of the engineer in charge without a structure or framework. Several research works study to further frame this situation. The publication [30] presents a framework for calculating maintenance duration to facilitate the capture and reuse of information in maintenance activities and to improve the effectiveness of the specified maintenance PSS based on the knowledge and tracking of key performance indicators (KPIs). Next, the paper [30] details a scheduling method that can be reused and extended, especially in the field of predictive maintenance. This method is able to take into account a wide variety of inputs and outputs, making it suitable for a wide variety of scenarios. The predictive maintenance indicators collected from the monitored machines are used to schedule service visits according to the plan in use. In order to serve equipment suppliers and other users with a wide variety of needs, a web services architecture is implemented.

2.6.3. Augmented reality based remote maintenance

Research on the topic of "digital reality" has been the focus for most of the last few decades. As the Fourth Industrial Revolution has progressed, innovative digital technologies have also benefited from the rapid development of information and communication technologies. The term "augmented reality" (AR) refers to a popular form of digital technology that adds computer-generated information to the user's real-world environment to enhance their experience. Azuma is widely regarded as one of the early innovators in the field of augmented reality (AR). His overview of the topic, the first of its kind, was published nearly two decades ago [31]. The growth prospects were considered extremely promising. To make AR a standard type of media, researchers must first overcome a number of obstacles, some of which are mentioned in a recent publication [32]. The development of user-friendly augmented reality (AR) applications and tools is a major hurdle that the research and development community must overcome.

Various publications addressing the AR-based maintenance component are available in the current literature. The vast majority of efforts focus on providing remote assistance for technical maintenance activities using a variety of AR-based frameworks. An example of a widespread use of remote maintenance assistance can be found in [32], which describes a scenario in which technicians are able to perform maintenance operations on robotic arm manipulators by following projected augmented reality (AR) instructions. Paper [33] presents another unique augmented reality framework that can be used to support maintenance and servicing operations. In the context of product service systems, [34] discusses another facet of AR-based remote maintenance (PSS). Therefore, the AR tools that have been developed can make it easier for manufacturers to integrate the PSS mindset into their product lines, adding value to those lines.

The paper [35] is a collection of works that investigate the current state of the intelligent maintenance paradigm by reviewing recent publications and extracting applicable empirical knowledge. A cooperative remote maintenance architecture is proposed in [36]. The research is motivating and of high quality, but the implementation of the framework relies on technologies and equipment that are now considered obsolete; the technician is limited in his mobility as he needs a PC nearby to view the AR instructions. In addition, the projection of text-based material is crucial to the instructions. Finally, based on the results of this study, the frame cues are not sufficient to guide repairs on larger and more complicated machines. Therefore, a stronger and more compact frame is needed to improve the mobility of the technician when working on the machine. A related work presenting a remote maintenance support system based on augmented reality can be found in a recent study [37]. The authors' commitment to creating a portable tool based on the use of a tablet PC is admirable. However, the use of frame markers is unavoidable, as shown in the study presented earlier, and can have a significant impact on the overall performance of the tool and, by extension, on the productivity of the technician in the shop or in the field.

AR-based tools proposed by the research community over the past two decades have continued to advance, but many still lack essential functionality. AR should be considered a core technology, as evidenced by the aforementioned advances as well as the practical deployment of these frameworks in real industrial environments and in vitro laboratory testing. Therefore, new features should be added to AR tools as they are developed in the near future. A good example is the system presented in [38], which provides an adaptive AR environment for the operation and technical maintenance of machines. The flexibility of this framework relies on the expertise of the experts working in it. A new framework using a haptic wrist tracking technique is presented, for example, in [39].

2.7. Global workflow

2.7.1. General system workflow

The workflow provided in the figure is a description of the methodology proposed in this work.

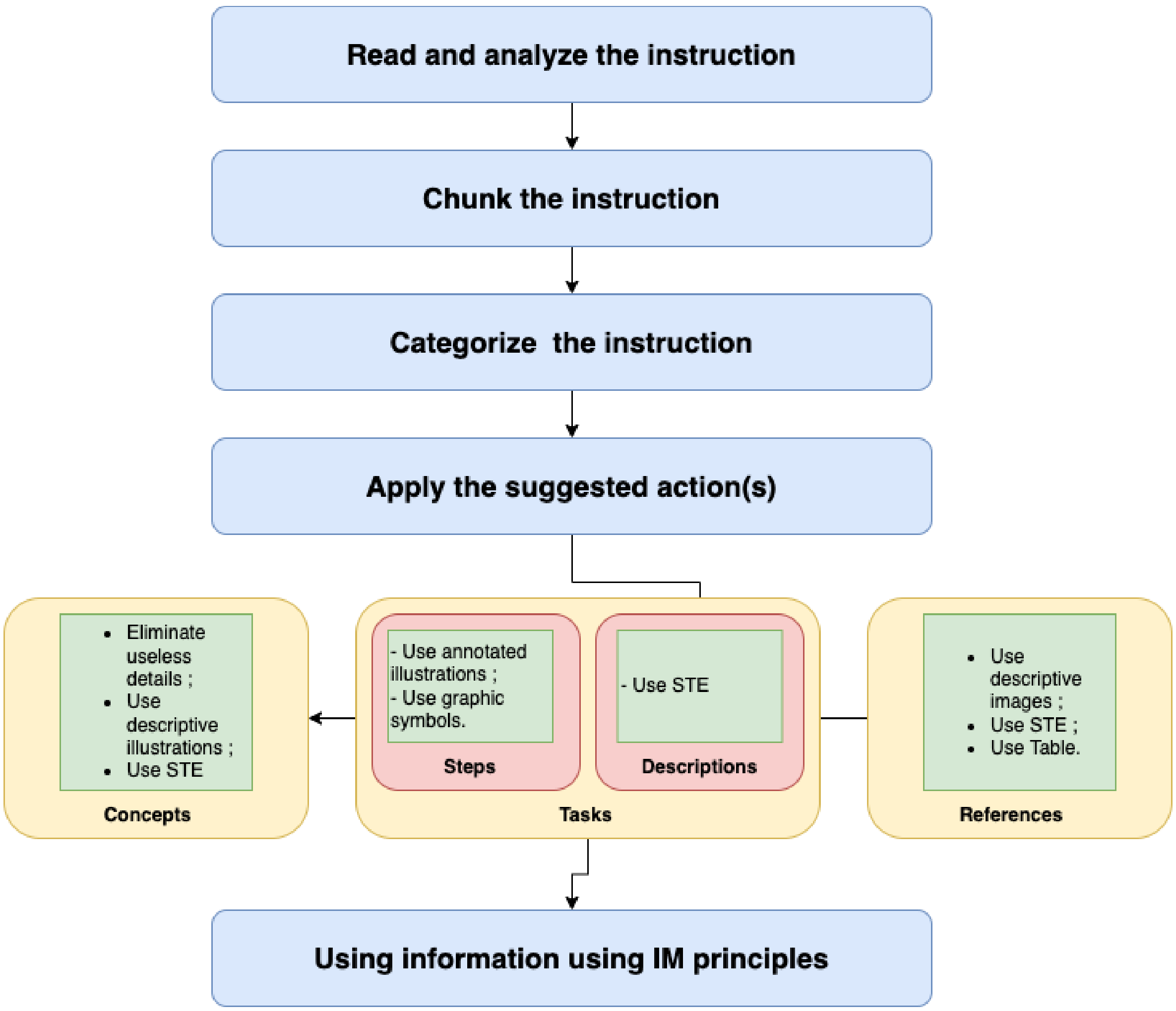

Figure 19: General methodology workflow

The first step in the proposed approach is to read and analyze the instruction to determine how it can be broken down into specific actions in the second step.

Then, each guidance element must be classified accordingly:

- concepts for abstract or evaluative information;
- tasks for procedural guidance broken down into steps and descriptions;
- references for concrete aspects.

Different conversion steps are proposed depending on the class to which the instruction belongs. Since it is difficult to replace text entirely with visual elements for concepts and descriptions, a text optimization technique is recommended, while the use of visual elements can greatly enhance the comprehension of procedural information presented in step instructions (e.g., annotated images, graphic symbols), in particular exploiting AR. Finally, factual data provided with reference information can be organized into tables. In instructions 1, 2, and 3 the action verbs (turn, pour in, check) can be replaced with graphic symbols with the same meaning, while the objects they refer to can be localized exploiting georeferenced signs (e.g. circles, arrows) in AR, and for the conditions text or 3D animations can be used. In instruction 4, text cannot be eliminated, but can be optimized using adequate strategies.

However, we have presented and analyzed a basic content structure according to the principles of information mapping (IM) [40], which can be modified by graphic designers to meet their needs.

The preliminary pillars of our methodology, detailed in the next sections, are as follows:

- The Optimization of text use, through Simplified Technical English (STE) [41];
- The Conversion, as much as possible, of the text instructions into 2D graphic symbols [41] (except convertible instructions (e.g., descriptions, concepts) that are provided in textual form using STE;
- Structuring the content, as regards information types (concept, task, reference) [42], and Information Mapping.

2.7.1.1.Text requirements: Simplified Technical English

Controlled natural languages (CNLs), sometimes called controlled languages (CLs), are a popular technique for making written instructions easier to follow. According to Kittredge [43], a CL is a form of natural language condensation that has been developed to achieve a specific goal, that goal usually being the creation of technical texts for readers who are not native speakers of the language used. As a rule, a CL will use only a certain subset of the grammar and lexicon of a language, supplementing it with specific terms that are linked to a technical subject terminology.

The main advantages of CNL are better human interaction, simplified translation and a more homogeneous and familiar representation of formal concepts. These advantages make it appropriate to use CNL to produce new digital manuals. Although CNLs have been around since the 1930s and have appeared in manufacturing environments, they are not yet widely used for technical documentation. Many large companies, including Kodak, Caterpillar, IBM, General Motors and others, began working on their own NLCs but eventually abandoned them in short time order. Relying on the STUDY learned at Caterpillar, Kamprath et al [33] propose to develop NLC and writing simultaneously.

2.7.1.2.Structured writing

The separation of content and form, the reuse of existing information and the publication on several channels are all possibilities offered by structured writing. The creation technique relies on specific criteria to produce coherently organized categories of information that can be reused in many circumstances and contexts. DITA and information mapping are two well established techniques in the field of structured writing. IBM's User Technology group released DITA in March 2001 [42]. Along with DocBook and S1000D, it is one of the most widely used document type definition (DTD) for organizing the content of documentation and technical manuals. However, research shows that DITA has now surpassed DocBook and S1000D [44] in terms of recognition. Topic orientation and information typing are DITA's two most fundamental ideas. The data collected is then broken down into manageable chunks (themes) that address a central question or concern. In addition, the information is characterized and classified according to its type, independently of its delivery mode. Each type of data can therefore be the subject of a specific output manual. Due to this, we used the three main categories of DITA information for differentiating instruction: concepts, tasks, and references. Although DITA is currently the most popular XML-based authoring tool, information mapping has been around for a while and has emerged as an effective approach to organized authoring. It's common to hear about "information mapping" and "DITA", however while the former is a process that gives you all the rules you need to write in a structured way, the latter is a technical approach to writing and publishing. The U.S. Air Force Systems Command funded the initial research phase that resulted in the Information Mapping approach. Its primary distinguishing characteristic is the substitution of discrete chunks of information, known as "Information Blocks," for paragraphs. In the sections below, we detail how we implemented information mapping ideas into our research and design of an augmented reality system for maintenance management:

- **Chunking:** The data must be decomposed into manageable chunks (blocks of information). Next, we decomposed the instructions into their constituent parts, or concepts, tasks and references.

- **Relevance:** Each section should focus on one major idea. Then, we opted for the plan of showing only one piece of data at a time according to the user's need.

- **Labelling:** A label must be provided for each section of the material to help the reader understand what they are about to read. We then propose to place a title and subtitle in the header of the GUI for each section.

- **Consistency:** All elements of a document, from paragraphs to tables, must follow the same standards. Once you have chosen a system for displaying data in the GUI, it is important to stick to that system in all generated documentation.

- **Integrated graphics:** Each image, graphic, and table should convey as much useful information as the text. Since the majority of information will be presented visually, the visual elements of the themes should be placed in the primary central area of the user interface.

- **Accessible detail:** It is important to put the relevant content in front of the reader's eyes at the moment he needs it. Thematic textual information can be located at the periphery of the interface (in this work, we propose to place it at the bottom).

- **Hierarchy:** The data should be structured in a hierarchical manner, with smaller units placed behind larger ones, and each group labeled appropriately. Then, to help the user understand where they are in the process, provide a table of contents with all topics structured in a hierarchical style.

2.7.1.3. Visual elements

New computer graphics interfaces, such as augmented reality and virtual reality, can profoundly change the delivery of technical content to the end user. Actually, in the past, text was the primary form of information on paper, with static tables, photographs, and drawings serving mostly as supplementary material. Head-mounted display devices (HMDs) are becoming more common and affordable, with features such as high resolution, embedded 3D real-world scanning, voice and gesture recognition, for example, Microsoft Hololens. In addition, augmented reality (AR) used on mobile devices can provide a low-cost, user-friendly method of creating technical documentation for SMEs. These tools allow you to create dynamic, interactive and complex graphical representations of data in digital form. In the Industry 4.0 era, visuals play a crucial role in the development of technical documentation, as they allow for personalized transmission of information (from non-specialists to highly skilled technicians). In the industrial context, AR or VR content has been suggested as a support for maintenance [20][45], assembly simulation [46][47]–[49], sometimes with tactile communication, and also to improve information delivery and perception in manufacturing systems [50].

In previous research, we examined the potential application of AR to assembly and maintenance guides. Specifically, we found that showing the operator a visual representation of the tasks to be performed and the method for performing them was a very effective means. The operator can benefit from the visual features of the AR for two different tasks: locating the necessary components and performing the procedure.

We have established five types of graphic components for augmented reality technical documentation:

1. **Simple 2D graphic elements:** These are simple graphical primitives, such as circles, lines and markers, which have no specific meaning but can be used to indicate directions, make simple notes and show where an element should be placed.

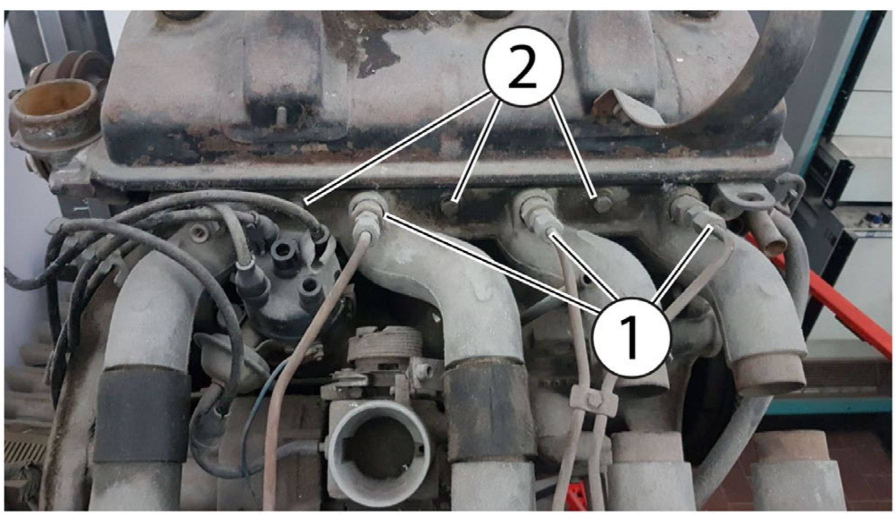

Figure 20: An example of using simple 2D graphic elements. Numbered callouts from automotive workshop manual [45]

2. **Icons and symbols:** They communicate something by adhering to a predetermined standard. Users can quickly and easily absorb the information conveyed by pictograms, symbols and icons.

Figure 21:Examples of international safety symbols. From the left: a mandatory symbol, a prohibition symbol and a warning

3. **Multimedia elements:** Possibly images or videos captured at the actual location or scene. Audio messages and/or other visual elements can also be added to enrich the content (text, icons, filters, etc.). Lately both pictures and video can be captured by cheap 360-degree cameras and the user can interactively change the point of view in the so-called cinematic VR.

Figure 22: An example of using multimedia elements. A picture is taken during the operation and used as instruction guide on a web platform [51]

4. **2D technical drawings and pictorial illustrations:** These graphical elements are ruled by technical standards (e.g. ISO EN 128-20,''Technical drawings, product definition and related documentation"). They specify the geometric properties and construction methods of the products. The following are frequent in the documentation for assembly and maintenance procedures:

    - Exploded views: used, for example, to display the internal components of an assembly and their location;

    - Technical illustrations: They are utilised under specific circumstances in an exposed environment (e.g. simplification of locations of specific parts to be handled). These illustrations are created by a variety of CAD (computer-aided design) programmes in various viewpoints and dimensions (2D OR 3D), and the export is typically done as an image (jpg, png...) or vector graphic (dwg,dxf...).

5. **3D navigable models:** These are simplified mesh designs (e.g. VRML, WEBGL, COLLADA) or graphical representations of products in a common CAD format (such as IGES, STEP or JT). With several options like rotation, zoom, cuts and movements, the user can quickly and interactively understand the geometry of the model. It is possible to achieve an even greater sense of realism by using photorealistic rendering. Users can view the 3D models in either a static or animated format to better understand the procedure (for example, opening a toolbox). Triangular meshes are the standard format for exporting models from engineering CAD systems, and animation capabilities are built into mesh editing software (e.g. 3DS MAX, blender, SculptGL, 3D slush ...). Most modern CAD programmes can produce models and animations without resorting to a separate programme (e.g. Catia composer by Dassault Systems).

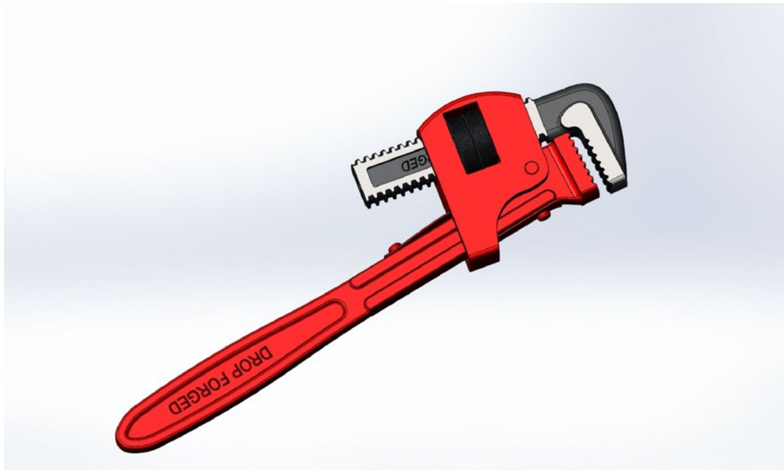

Figure 23: An example of using 3D navigable models on mobile devices

In the following table, we compare the five types of visual elements in terms of their ability to meet the criteria of intuitiveness, graphical availability, efficiency of creation and updating, standardization, and potential deployment in augmented reality interfaces:

Tableau 1: Comparison of visual elements categories for AR technical documentation

	Intuitiveness	Availability	Ease of authoring	Ease of updating	Existing standardization	Eligibility for AR deployment
Simple 2D graphic elements	High	Always	High	High	No	High
Icons and symbols	Medium	Always, but limited	High	High	No	High
Multimedia elements	High	Not always	Medium	Low	No	Low
2D technical drawings	Medium	Not always	Low	High	Yes	Low
3D models	High	Not always	Low	High	No	Medium

Even when produced by a 3D CAD software, drawings demand a significant amount of creative work. Indeed, in industry, they are designed by a technician or engineer to fulfil a particular need. For example, disassembly procedures may require a unique sequence of steps, with model components marked with distinctive colors. Most of the effort is also spent for the indication of the part to be operated. Drawings can be considered not optimal for an AR documentation because they do not exploit appropriately the integration with the real world, and cause visual occlusion for the user. Specifically, their usage in AR will be at user request and for short time span. On the other hand, 3D computer graphics models are very intuitive for the user, especially if animated. However, they are not always available in a AR compatible format. The authoring time needed to create from scratch and/or convert from CAD is relevant and increases with the complexity of the product.

In the literature presenting augmented reality instructions, 3D models and animations are frequently used. But still, any mistake in geometric model or tracking will be immediately apparent to the user due to the fact that the virtual objects are shown on top of the real ones. Because of this, producing a high-quality augmented reality 3D model takes long time in term of authoring. Photos and videos taken at the scene by the user can be highly helpful and are frequently utilised in user-generated wiki manuals like iFixit [51] or on YouTube repair channels. However, sometimes multimedia acquisition is not possible in an industrial context due to factors such as accessibility, safety or security. Photos can be acquired far more quickly than CAD models, but only when appropriate permissions are granted, the scene is prepared, and post-processing is completed. However, it is well known that multimedia can become obsolete and must be reacquired if the product or procedure is changed. Furthermore, occlusion makes it challenging to incorporate them into an AR scene, much like 2D drawings. The usage of 2D visuals and symbols is common in both the theoretical base and the practical application. Using symbols reduces authoring time since a technical writer has just select an appropriate symbol from a predefined vocabulary. The symbols have the potential to be very adaptable to product changes. Symbols in augmented reality documents may be placed anywhere in the environment (e.g. displayed near a component for indicate an operation or in a fixed region of the GUI). Unlike physical objects, symbols do not always have to be placed precisely, minimizing the authoring effort. One possible problem is that they are not always obvious and often require additional training. Additionally, there are currently no established guidelines to follow when documenting AR.

For this reason, and because of its many advantages over other visual elements, particularly in terms of creative effort and integration in an augmented reality context, we chose to create a strategy focused on 2D symbols. Considering the need for standardization, we conducted a study to identify a set of visual symbols that may be utilized in augmented reality (AR) to depict upkeep guidelines [41]. We are convinced that comparable studies will encourage the scientific community to standardize graphic symbols for the documentation of maintenance operations. Still, 2D symbols are not enough to convey all the necessary details about a task; other information, such as the location of relevant components, is needed. The information may be given without augmented reality by utilizing a picture that has been tagged, but in the future, augmented reality applications will rely on a live feed from the camera that includes referenced graphic signs used for localization.

2.7.1.4.Design guidelines

The standards that an application must meet to satisfy its users are extremely high. Application designers use established design guidelines (DG) when creating the application's user interface to ensure compliance with this standard. We introduce three broad DGs that have gained widespread acceptance in the realm of UI design. First, there is DIN EN ISO 9241110 [52], which provides seven guidelines for UI development. Some such examples can be found in the theories of Nielsen and Molich [53] together with the 8 guiding rules of interface design [54]. Here are some of their similarities:

- **Simple Design:** an app should contain just the features needed and required, None more, none less;
- **Feedback:** Each time a user is interacting with the system, the system must provide feedback that communicates the current action to the user;

- **Preknowledge:** Knowledge already acquired by the user, such as common concepts, must be integrated;

- **Consistency:** The standards must be maintained, and the system must be consistent throughout the entire application;

- **User Mode:** Several modes (tutorial, beginner, intermediate, advanced) should be available in the system to accommodate users of different levels of expertise;

- **User Control:** The backward, forward and start of session navigation options should always be available.

- **Help:** As soon as a user makes a mistake, the system should alert them and provide an easy method and explanation;

- **Error prevention:** Errors should be avoided by the system, for example by prompting the user to take some sort of action before proceeding;

- **Individualization:** The system needs to be flexible enough to meet the needs of individual users, such as support for many languages;

- **Help & Documentation:** Support needs to be accessible. In a timely manner, the system should provide assistance that is simple to understand.

2.8. COMPONENTS AND THEIR INTERACTIONS

Each part of the application's technological architecture is connected to each other in a way that guarantees the application's stability, order, and organisation. The proposed augmented reality application approach will guide the operator through each step of the process, from following instructions to implementing the suggested action. Here, we lay out the technical framework of the application and its major components in the form of a flowchart.

- **Visualization technology:**

This component provides a visual representation of digital data in relation to its physical environment. Head-mounted displays (HMDs), wearable devices (HHDs), static displays, and projectors are the four main visualization technologies often used for augmented reality (AR) systems[55]. Depending on needs, the visualisation system can be installed in a stationary or mobile device.

- **Sensor system :**

Data is collected from the environment by the sensor system. The camera(s) serve as the primary input for the majority of augmented reality systems. Stereo cameras allow for the detection of depth. Ultrasonic or infrared sensors are alternative techniques for collecting depth data[56]. Several sensors, such as gyroscopes or accelerometers, are used by mobile systems (HMD or HHD) to detect the orientation and position of the screen[57].

- **Tracking system :**

The AR tracking system allows for precise placement of virtual items in the real world. The most common type of augmented reality uses markers. Some locations have physical markers. With the help of these augmented reality markers, we can more corresponding point the location of a virtual object. The recognition of markers is affected by dirt, mechanical abrasion, or lightning conditions despite the technology's maturity and understanding. Systems that use natural markers, also known as markerless systems, do not rely on any external markers tied to the actual world to identify the precise position of virtual objects[58], [59].

- **User interface :**

With the AR user interface, the user can interact with the system and receive feedback in both directions. A variety of technologies, including as force feedback[60] and aural signals (acoustic cues)[61] are deployed. Some of the most common ways users capture data include gesture recognition [62], eye tracking and direction of gaze[63], voice recognition[60] and discrete hardware solutions. The term "discrete user input hardware" can refer to the mouse, keyboard or hand scanner.

- **Processing unit :**

The software needed to run the AR system must be executed by the processing unit. Also, it is the connection to additional data sources from which information can be gathered or delivered instantly.

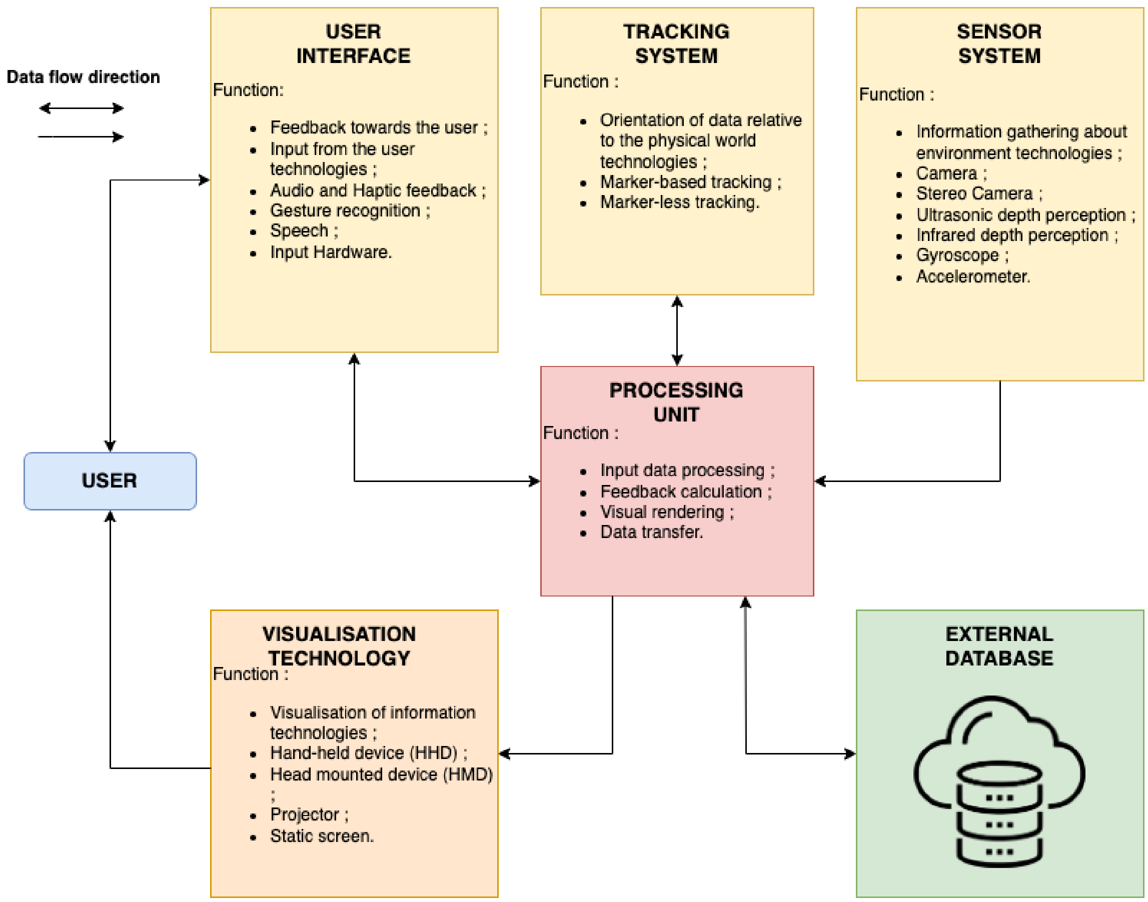

Figure 24: Components and their interaction of AR system

2.9. Implementation

2.9.1. Proposed system architecture

The scope of this study project is centered on the design and development of a maintenance assistance method, as we have seen in the previous paragraphs. This solution, remote and in real time, based on augmented reality, allows the development of new communication modes between expert engineers and field technicians. In concrete terms, the necessity for setting up AR scenarios might be eliminated, which would significantly reduce the time and effort required to produce such content. In addition, by using the suggested framework, professional engineers are able to direct technicians and operators in less likely maintenance and repair operation (MRO) scenarios, thereby overcoming some constraints. The methods used to solve the identified scientific gaps will be explained in detail in the following sections in order to achieve the stated technical requirements. The diagram that follows illustrates the flowchart of the proposed system:

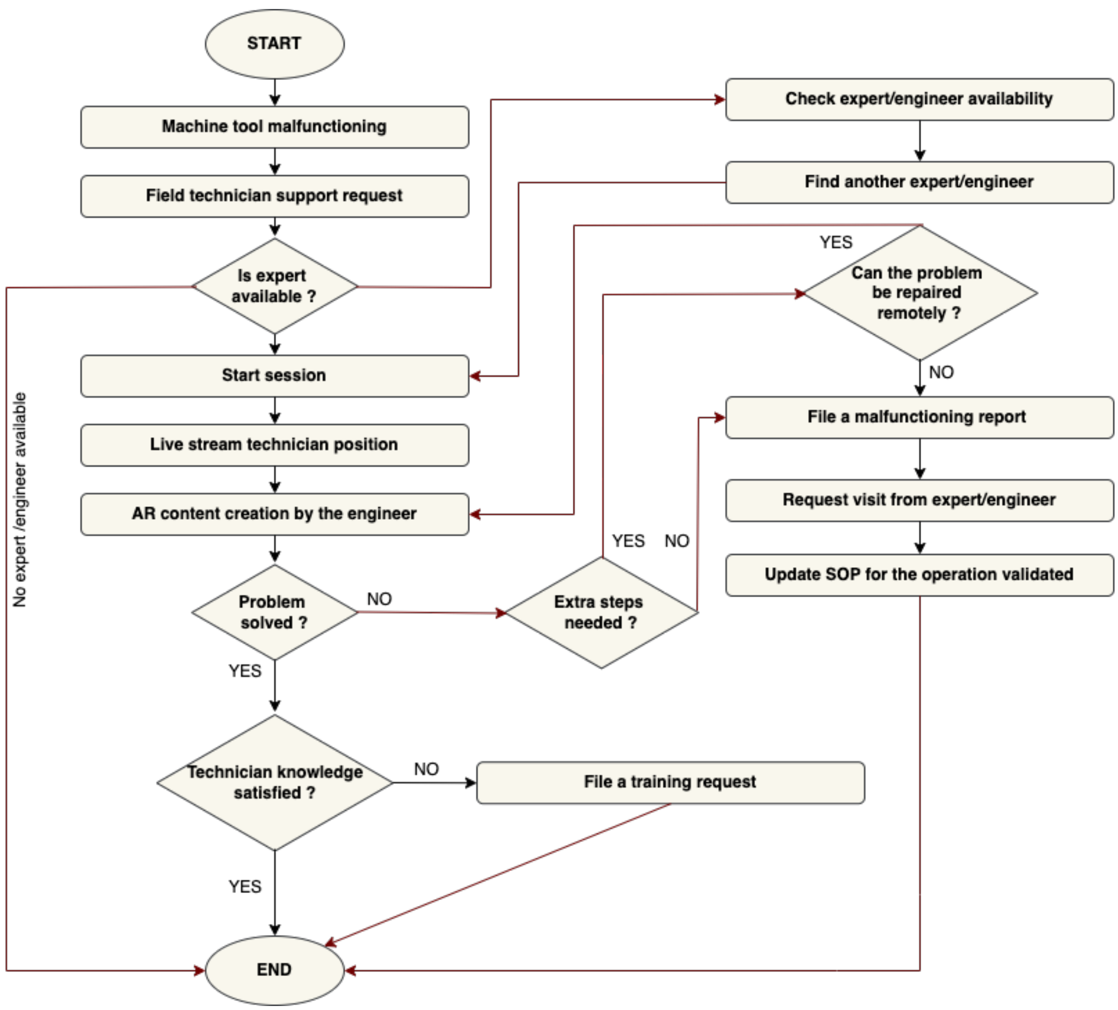

Figure 25: Flowchart of the proposed system

As soon as a dysfunctional machine tool is identified, a chain of events will start. The operator in the workplace, equipped with a head-mounted display device (HMD), then requests assistance from the expert engineer. It is underlined that the two parties do not have to share the same physical location. To be more specific, technicians working at the workplace can establish a remote connection with the maintenance department responsible for technical support using dedicated communication protocols. As long as there is a connection between the two participants, a live video stream from the device used by the technician working in the workshop is transmitted to the device used by the expert engineer. This can be performed in the form of a real-time teleconference between the two parties involved. So, while the expert engineer is watching the video stream, the shop-floor technician is able to provide comments, which will assist the expert engineer in gaining a deeper comprehension of the problem with the machine tool. As soon as the engineer has a complete understanding of the problem, they are able to generate on-demand augmented reality content, which will be projected in the FOV (Field Of View) of the shop-floor technician. During the live-video casting from the technician, it is underlined that the gadget is also capable of performing a 3D scan of the area around the technician. As a result, the expert engineer is able to correctly record the 3D content in the technician's field of view with even greater facility. The design of the framework can be created by means of a platform, which allows shop-floor technicians to connect with one another and make requests for assistance from technical experts in real time. It is important to add all the steps already described throughout the teleconference process between the two parties in an information base. In our approach we recommend adding the additional steps to the standard operating procedure of the intervention made. This way a new version will be updated for a future intervention. All this to ensure that no time is wasted and to reduce the cost of the intervention. On the other hand, the satisfaction of the technician is to be checked for the same reason. The technician can always have access to a training session regarding the intervention done. Using the platform's 3D tools, the expert engineer can provide comprehensive support to the technician via the communication interface. Consequently, identifying the platform's structure is important. The structure of the proposed methodology is shown in Figure 9. A look at the diagram demonstrates that the Cloud Platform is composed of several parties and a support engineer who is an expert for assistance.

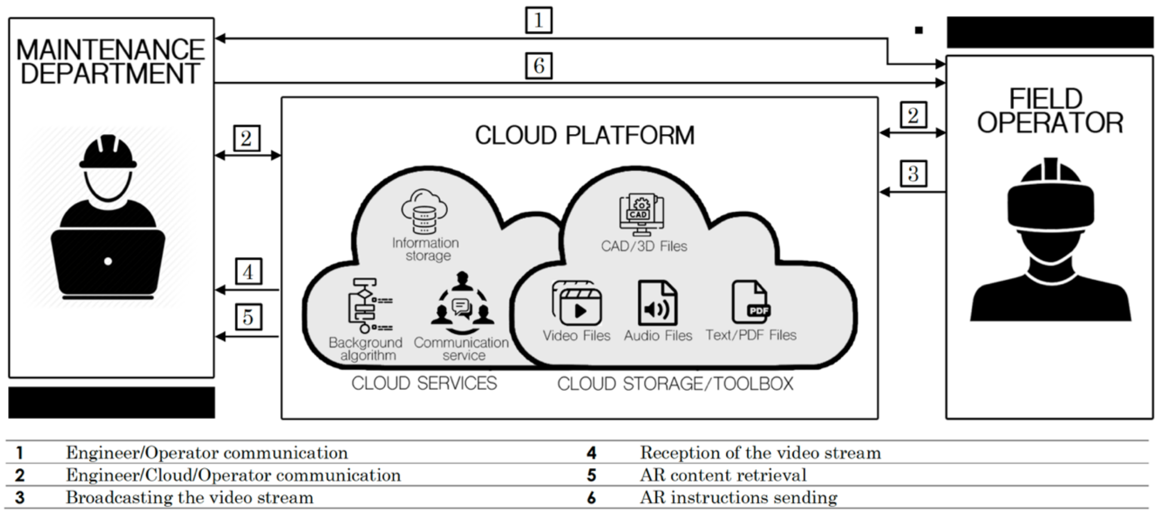

Figure 26: Proposed system architecture and steps sequence

2.9.1.1.Cloud platform

The application approach suggested for this study consists mostly of a cloud-based remote maintenance application. The proposed application involves a number of parties and departments. When necessary, the cloud platform provides effective communication with different departments as well as between the expert and the technician. There are two domains that constitute the cloud platform. It is both the communication and the storage of data field. As was said before, the communication domain is utilized to pair expert engineers with shop floor technicians and set up interaction between the two parties. The Cloud Database serves as the primary data storage area where all the data, including the 3D geometries, are stored in SQL tables. Hence, the Cloud Database can be considered the actual data storage domain.

Cloud platform can provide several benefits for the AR remote application:

- **Scalability:** The Cloud platform provide adaptable resources that can scale with demand. This is especially critical to our approach knowing that the application may experience increased usage due to a special operation.
- **Reduced Latency:** Data centres hosted on cloud platforms can be located closer to end users, hence reducing latency. This can lead to less waiting time and quicker AR rendering.
- **Cost-effectiveness:** Hosting a remote augmented reality (AR) application in the cloud can be less expensive than on-premises hosting, as cloud platforms often use a pay-per-use model.
- **Security:** Cloud platforms typically have robust security measures in place, including firewalls and encryption, which can help protect sensitive AR data.
- **Accessibility:** Using a cloud platform, augmented reality remote applications can be used from any location with an active internet connection. That signifies that the app can be accessed from various devices.

2.9.1.2.Maintenance online session

After seeing a malfunctioning equipment, shop floor technician can connect with the expert using a cloud-based platform and a mobile device. As soon as the shop-floor or field personnel determine that a machine is not performing properly, they are able to use a mobile device to access the cloud platform and convey their findings to the expert. A communication domain is generated for each and every session that is created. With the construction of the communication domain, the two parties are able to exchange tasks and descriptions with one another.

2.9.2. Proposed graphical user interface

The platform's most important structural component is its online connection and user interconnection structure. Specifically, the system operates as a cloud-based platform that facilitates communication and data sharing between expert engineers and field technicians in the field or shop floor. It is underlined that no limits exist on the nature or quantity of information that can be shared. In addition, live teleconferencing support can improve usability by facilitating instantaneous interaction between all parties. The framework has a teleconferencing function to facilitate better interaction between the concerned parties. Activating this function will cause a live video feed from the expert engineer to be projected directly into the user's field of view (FoV). Consequently, it is anticipated that the two-way communication will be more effective because the technician may perform several maintenance, repair, and overhaul (MRO) activities concurrently. Regarding the exchange of information, the platform is linked to a cloud-based database. The database includes a specific section where certain 3D geometries are stored, which can only be imported into the AR scene by expert engineers. An MRO digital toolbox can be assembled from the most used tools in maintenance operations. The complexity of machine tools, however, may eventually necessitate the use of more specialist equipment. So, the specific tool can be added digitally by the expert engineer via the GUI section: Create tool.

We illustrate the proposed GUI for joining an online maintenance session in Figure 10. At the top left corner of the Interface, there is a dialogue box where the user can select a session to join. The user is required to log out of the session after it has reached its conclusion. The master engineer can retrieve the necessary tools from the Cloud platform and place them inside the FOV of the technician using the action: Drag and drop by pressing the corresponding buttons in the bottom left corner of the interface. When an engineer needs a specific tool that isn't in the Cloud's standard toolbox, the engineer can simply upload a 3D model. In such a situation, when the Expert clicks on the "+" icon another create function with which the engineer adds the appropriate element with the right geometry in a suitable filetype along with relevant info and a description of the tool. Cloud database uploads are now limited to file formats authorized by the AR application. The reason for this limitation is due to the development tools used for the application's framework. Unity 3D game engine is utilized for its creation and supports the following 3D geometry model file formats: .fbx, .dae (Collada), .3ds, .dxf, and .obj. The background algorithm is in charge of transferring the geometry to the Cloud Database and creating a new record in the SQL Database. The SQL database is built by taking an "ontological" approach and so is its exploitation. As a result, the expert will have predefined choices and action suggestions to further facilitate the creation of the AR scene. After an analysis of the different maintenance procedures frequently deployed in industrial units, a list of tools has been established. These tools are imported into the Cloud Platform toolbox.

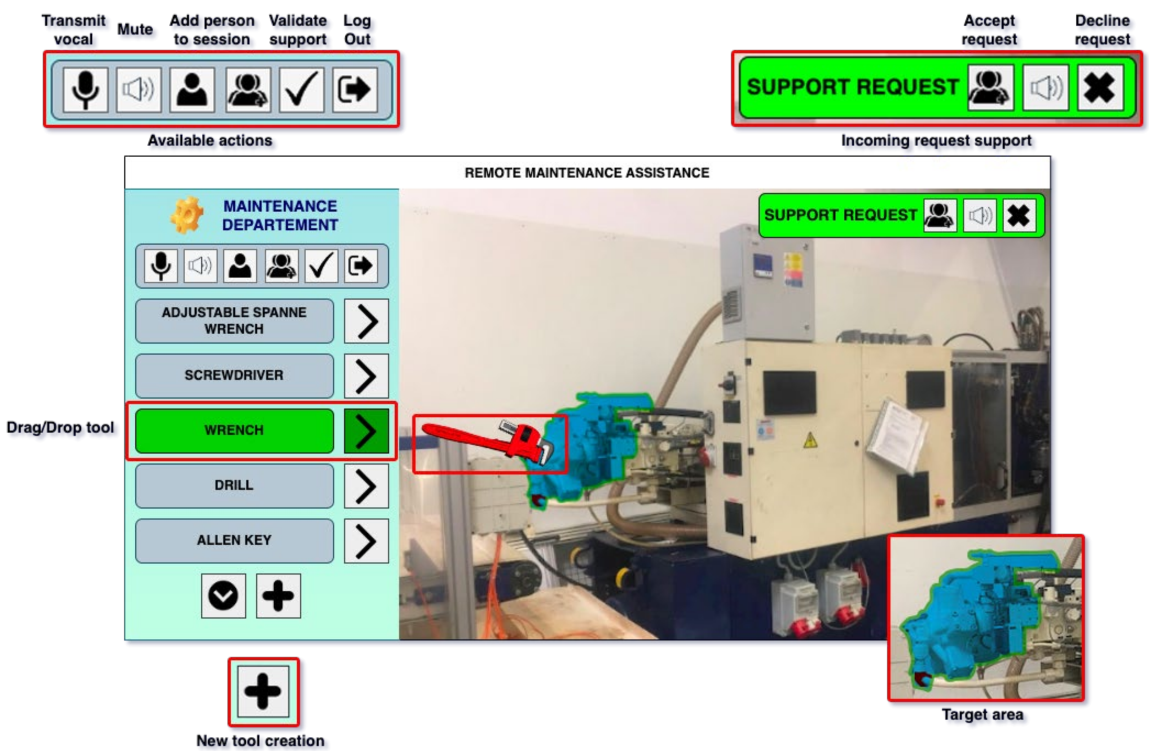

Figure 27: The proposed GUI for remote maintenance assistance session

Teleconference is an essential feature within the architecture of our application. This functionality ensures a total communication between the expert and the technician. Several solutions can be deployed, each according to its characteristics. We cite for example: Skype, Agora.io [64] and GIGA Video [65].

For the communication framework, we think to retain Skype which optimizes the criteria of our application. With this solution, the teleconference will be optimal and personalized in terms of exposition and organization of the essential elements. Thus, in terms of quality, Skype seems to be the most efficient.

However, for the implementation of such a solution and its direct integration on our HMD another problem arises. The user will alternate between two applications at the same time. One for teleconferencing and another for remote AR assistance. The two other SDKs (Software Development Kit) (GigaVideo and Agora.io) can still be implemented in our application framework, but in terms of cost, they are not free; which poses an additional constraint.

Moreover, an API model is to be developed to unify the two components: communication and remote AR assistance. The custom model is based on the UNET API and satisfies the application framework. It is a server network model provided by Unet. It helps to build an API network structure supported by Unity 3D[66], [67]. Thus, Unet allows, through high-level scripting APIs, to eliminate details and low-level cases by organizing the network through these APIs and meeting the known requirements.

In our approach, we recommend to choose a dedicated server that hosts the two users (Expert(s) and Technician(s)). This system thus ensures a structure and a synchronization between the connected parties. This module was chosen for the following reasons:

1. The identification parameters and the connection status of users can identify and control themselves in one place;
2. The model can detect and process information and incorrect data entered or added to the interface or already exposed in the framework;

3. It facilitates the addition of different elements by both parties regardless of the extension;

4. It can accommodate a large number of users.

The features of the server are described in the following table:

Tableau 2: Processing capacity of the dedicated server

Processing capacity of the dedicated server
Login ID
Transfert and synchronization of information flow
User Login/Logout Management
Upload and update content
Creation of communication channels

Mainly, users can log in and use any user interface (HMD, PC, Smartphone...). A PC is the host of the servers. One or more servers are required for user access to the application. Data synchronization is illustrated below:

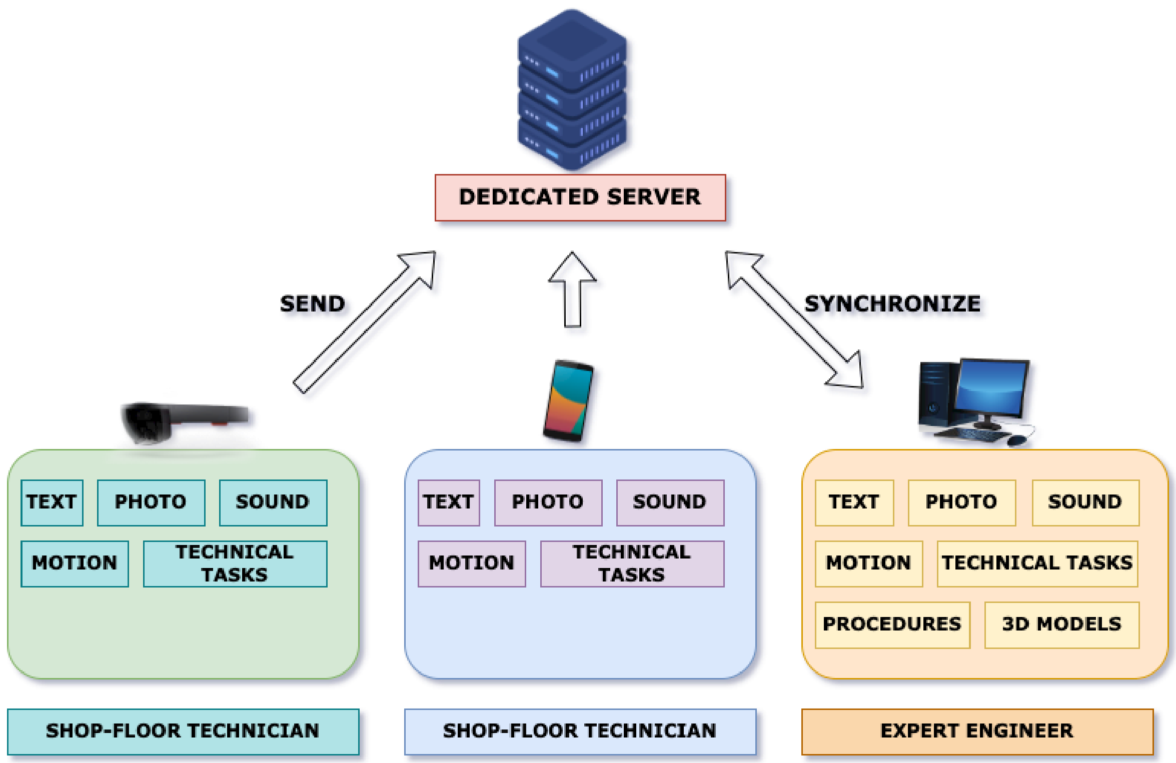

Figure 28: Dedicated server synchronization process

The data that are sent, as mentioned in the previous paragraphs, are mainly in the form of text, images, voice notes and 3D files.

The platform is designed in such a way that it is adaptable to several devices including mainly HMDs, Smartphones, PCs. For our approach, two are, in our view, effective. Microsoft Hololens can be integrated as a HMD (dedicated to the technician): To take advantage of the various benefits offered by this HMD. On the other side a PC for the Expert. The content of his screen (audio and video) is transmitted to Microsoft Hololens. By opening this window, the technician will have access to the content created by the Expert.

2.10. Discussion

The presented work is an application approach for an AR system for maintenance operations in the context of industry 4.0. This system is designed in such a way that it can be accessed by several people in the department regardless of time and position of the users. This connection can be simultaneous by all parties for a relevant discussion and subsequently the implementation of the intervention after a detected malfunction (planned or unplanned). Our approach also aims at the implementation of the application in several portable or static devices. These devices are mainly HMDs. And the so-called handheld devices (smartphones, tablets...) and PCs (portable or fixed). They are devices that are often used in AR systems.

Generally, AR applications integrate the Tracking functionality for a marking of the AR exposure elements. For this reason, in this study, the use of Microsoft Hololens is favored. This device does a full scan of the environment in addition to its unique spatial recognition. It is always emphasized that the use of such a device is dedicated in our case to field technicians, with which it captures its environment. The expert bases on this capture to add the virtual content to the scene projected on his screen.

The first step was the design of a general process for our system in order to set the context for the application. This process mainly describes the global steps for an efficient AR application, starting from the analysis of the malfunctions and arriving at the total implementation of the intervention. At this stage information mapping (IM) was introduced. IM helped us to understand the nature of the content to be presented on the real environment and its optimization (STE, 2D graphics, content structure...). The structuring of the text used was a mission to adapt it to our application framework. A study was made to decompose the main elements of our framework (Text, 2D, 3D), to know well the priority elements. In section 4, the Architecture of the AR system and the information flow was established. Before moving on to a full description of our approach in Section 5, our architecture for AR Maintenance Support establishes a flow of steps, intervention logic and all Action steps. In this step, we designed a scenario that implemented the SOPs as a preliminary step. Then the architecture was tested by analyzing the different behaviors of the participating parties in the same scope (Maintenance Department). Then, based on the comments given by engineering colleagues a final relevant version was established. The same logic after a functional analysis to have the final communication structure of our approach. The cloud platform is the core of this structure, it was dedicated for the storage of RA exhibit elements so it is a base for interactive communication between the parties. The GUI framework represents the final step of our approach. This interface gathers the requirements posed within the communication structure by ensuring the addition of 3D elements, the preparation of the toolbox for interventions. Thus the assurance of a communication channel (teleconference). Several options are proposed from Adding Tools to Transferring Voice Notes. At this stage feedback is collected for a final version of our proposed GUI framework. Another strength of the proposed approach is the ability to create an online session. The Unet API provides these sessions based on the Unity 3D software by connecting multiple users in the same location. In this respect, other approaches [14], [18], [35], [36] present other application examples. However, these visions are limited to space and hardware constraints. For example in [35], in the industrial context, the technician or expert must be on site with a PC and a separate camera. This system is based on markers (tracking) as object detectors which strongly links the efficiency of the system to the quality of the camera hence a less efficient performance in case of presentation of some parameters and conditions (Noise, dust, low light ...).the performance of such an application strongly depends on these parameters. Moreover, our proposed framework uses newer devices that can make the experiment applicable in any condition. The other frameworks proposed in the approaches already analyzed, the augmentations are limited to the display of simple elements like arrows or text boxes. On the other hand, our approach can learn about objects through Microsoft Hololens [71].

2.11. CONCLUSION

Throughout this paper, several research works in the field of remote maintenance have been analyzed and examined in depth. This analysis shows that most of the established approaches lack a vision of real-time interaction. this is where our motivation for the production of this work comes from. indeed, different steps for the creation of a system for the management of remote and real-time maintenance interventions based on AR have been presented in detail. Moreover, such an approach helps more to build an interactive and collaborative environment between two very essential entities in any industry: Expert and technician. This work provides a tool for content creation in zero time. On the other hand, its implementation will have an effect on the different maintenance indicators. However, it is always stressed that this is a rich field for future improvements. As we have seen in the GUI creation part, Unity 3D remains an indispensable tool for the implementation of augmented reality and virtual reality (VR) applications. To this end, future work could focus on the design and development of more adoptive maintenance operation environments for different levels of expertise of the maintainers from experts to beginners.

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CHAPITRE 3
L'INTÉGRATION DE LA RÉALITÉ VIRTUELLE DANS LA MAINTENANCE : UN ENVIRONNEMENT DE FORMATION DES OPÉRATIONS DE MAINTENANCE.

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3.1. RESUME EN FRANÇAIS DU TROISIEME ARTICLE

La réalité virtuelle (RV) et la réalité augmentée (RA) offrent de grandes possibilités pour la maintenance industrielle. Toutefois, le développement de divers systèmes de réalité mixte (RM) est limité, en particulier pour les applications de formation aux opérations de maintenance et aux interventions. Pour une fraction du coût des approches de formation plus conventionnelles, la réalité virtuelle (RV) peut fournir des environnements de simulation importants pour l'apprentissage des compétences, qui sont à la fois interactifs et immersifs en trois dimensions. Des études théoriques montrent que ce type de formation immersive est supérieur à la formation standard sur ordinateur pour l'enseignement des tâches procédurales. Tout cela, en raison des différentes capacités technologiques ou de l'incertitude, en particulier dans la perspective de la sécurité au moment du déploiement. Nous présentons les différentes étapes de la création d'un environnement virtuel pour une opération de maintenance. Notre approche pour le présent travail consiste en la conception et le développement des éléments de l'environnement. Nous avons suivi une approche structurée pour la création d'une architecture complète. Le potentiel d'une telle application consiste concrètement en ses effets

en cas d'implémentation dans des opérations à haut risque : l'industrie minière par exemple. Grâce à ce cadre, plusieurs fonctionnalités seront ajoutées au processus de formation. Ce dernier sera plus efficace, plus flexible et plus adaptable aux différents niveaux d'expertise. De plus, il assurera un déploiement efficace tout en respectant les normes de sécurité.

Ce troisième article, intitulé « *Integrating virtual reality and augmented reality in maintenance: An environment for maintenance training operations.* », fut essentiellement rédigé par son premier auteur Haitam Ichou qui a également réalisé toutes les mises en scène et les conceptions 3D présentées dans cet article. Le premier auteur a également écrit les parties concernant l'état de l'art et a fait l'analyse de l'architecture proposée. Haitam Chaouki est le second auteur de cet article. Il a fait une grande contribution au niveau des conceptions et des animations en utilisant le logiciel Unity 3D. Monsieur Noureddine Barka et Monsieur Tawfik Masrour sont à l'origine du projet de cet article en proposant l'approche et la méthodologie de l'application ainsi Monsieur Noureddine Barka a contribué à l'amélioration de la rédaction pour la version finale.

3.2. TITRE DU TROISIEME ARTICLE

Integrating virtual reality and augmented reality in maintenance: An environment for maintenance training operations.

3.3. ABSTRACT

Virtual reality (VR) and augmented reality (AR) offer a great opportunity for industrial maintenance. However, the development of various mixed reality (MR) systems is limited especially for training applications for maintenance operations and interventions. For a fraction of the expense of more conventional training approaches, virtual reality (VR) can provide important skill-learning simulation environments that are both interactive and immersive in three dimensions. Theoretical studies show that this type of immersive training is superior to standard computer-based training for teaching procedural tasks. All this, due to the different technological capabilities or uncertainty especially in the perspective of security

at the time of deployment. We present the different steps to create a virtual environment for a maintenance operation. Our approach for the present work consists in the design and the development of the environment elements. We followed a structured approach for the creation of a complete architecture. The potential of such an application consists concretely in its effects in case of implementation in operations under high-risk conditions: the mining industry for example. Thanks to this framework, several functionalities will be added to the training process. The latter will be more efficient, flexible and adaptable to different levels of expertise. In addition, it will ensure an efficient deployment while respecting safety standards.

3.4. NOMENCLATURE

MR	Mixed reality
VE	Virtual environment
CAVE	Cave automatic virtual environment
MTR	Mean time to repair
SOP	Standard operating procedure
MTBF	Mean time between failures
TRS	Synthetic rate of return
TRG	Overall rate of return
WI	Work instruction
BOYD	Bring your own device
LMP3	Laboratoire des matériaux, produits et procédés de pointe
OEM	Original equipment manufacturer

3.5. INTRODUCTION

The introduction of Industry 4.0 and its remarkable development in the last two decades has materialized rapid changes that could remove several barriers within industrial units. All this has been done by implementing engineering solutions and referring to digital technologies [1][2] for an adaptation of manufacturing processes as well as the immense change of business models. The core and central element of this factory of the future targeted by Industry 4.0 is the human being [3]. This vision also adopts that the operators have an essential function in the intelligent factory, since machines cannot replace human capacities and intelligence. Moreover, this intelligence consists in the flexibility and adaptation of the operator to solve unplanned problems and breakdowns, thus, going beyond the execution of application tasks that require interaction with machines. Taking advantage of the speed with which intelligent production systems can be set up and then generate a lot of information, the workforce should use innovative technological systems that make the details of the mission easier to see.

Information systems and technologies play a very important role in the architecture of industrial maintenance in the context of Industry 4.0. Today, and thanks to mixed reality [4], an exposure of different data helping operators to validate all kinds of tasks has become possible. Here, we are talking specifically about the exposure of computer-generated data in a virtual environment as augmentations in Real Space. Because of its adaptability [5], realism of experience [6] and ability to simulate potentially dangerous operations and environments [7] (which is the case of this paper), virtual reality (VR) has emerged as a promising option for learning and training [8]. Yet, the assistance of virtual reality (VR) in the workplace can reduce the mental and physical effort of technicians while increasing many other parameters such as productivity, quality, and safety in the workplace [8]. Despite the potential of combining AR and VR into a single standardized platform, which could lead to savings in development time and training as well as deeper integration of safety and security aspects into an organization's strategy and methods, these ideas have so far been studied independently.

The benefits of virtual reality (VR), particularly head-mounted display (HMD) based solutions, lie in the fact that they provide operators with instantaneous and situational information during operation. In addition, VR can actively enhance safety by providing warnings and other important information in specific contexts. Furthermore, if information is displayed incorrectly, virtual reality can present safety risks by distracting the user from real-world hazards. Due to the significant hazards and risks associated with industrial operations, it is critical that VR solutions are robust, adaptable and effective. To determine the most effective methods of presenting information and interactivity to access AR material, developers of AR solutions for the industrial sector should iteratively evaluate several approaches. Text, audio, video, photos, and 3D models are all included, as well as actions such as navigation, message acknowledgement, and information retrieval.

To date, little effort has been made to standardize the format and presentation of technical information in augmented reality and virtual reality applications [9][10]. Due to the risks associated with real-world evaluations and the technical constraints of HMDs, the development of AR/VR solutions is typically halted at the verification stage. As new technologies become usable in industrial maintenance, the technical hardware must be adapted to meet the specific requirements of individual users and their particular environments, objectives, and devices.

In this paper, we present our approach on the use of virtual reality (VR) to facilitate maintenance training. We focus on the application of VR technology to facilitate the design and preparation of the training process related to maintenance operations. We propose an approach to create a VR-based experimentation environment that facilitates the selection, implementation and simulation of a maintenance operation. This involves the preparation of the preliminary architecture, the design of the environment elements, and the integration of animations and simulations.

We propose an efficient VR environment, capable of setting up the different pillars of a virtual maintenance workshop of a manufacturing plant and subsequently visualizing the maintenance instructions of the corresponding failure modes, in a portable and vivid way on the dedicated device of the operators. An environment was prepared for this purpose, by designing our maintenance repair unit. First of all, the object of interest or maintenance asset is positioned as it is handled and visible to the user and the same for the different 3D elements used in the system. For our case, a simulation of a motor disassembly operation is put into action. The operator (equipped with his HMD or smartphone) throughout the loop of interventions will be guided by the standard procedure of operation of disassembly of the engine by giving him the opportunity to choose the tool to use, the spare part if necessary and the exact location of the manipulation. The environment is easily controlled by the operator in 360° allowing him to move freely in his space to complete the asset maintenance procedure. When the maintenance is completed, the system sends a confirmation message. The contributions of this paper are summarized as follows:

- Reduce the consequences of the sources of risks linked to the mining industry (noise, dust, visibility, heavy loads, etc.) and to ensure the health and safety of the operators by offering them a first experience in the field to master the different operations.

- A support system structure is presented, which can be used by different levels of expertise from unskilled operators to expert engineers. A training tool in case of unavailability of support (e.g. night shift): decision support tool.

- The platform can be exported for run on HMDs or VR headsets or smartphones. This is a low-cost investment but has a very significant effect on maintenance indicators and production costs.

- To reduce the time spent looking for information, the proposed framework can use virtual reality features to replace paper-based instructions.

- It is envisaged that our approach will minimize the knowledge gap that currently exists between maintenance operators and manufacturers.

The remaining parts of this work are organized as follows. In Section 3.6, we explore representative works focusing on virtual reality applications that are utilized for maintenance training sessions within the context of Industry 4.0. On the other hand, section 3.7 contains a detailed description of the context of the realization of the project of this paper by specifying the scope of implementation as well as the targeted objectives. While in section 3.8 a detailed description of the proposed methodology is presented. In addition, we presented in section 3.9 the tools used to create the environment for an optimal implementation of our approach. In section 3.10, we made a structured presentation of our designed environment, moreover the description is made by scene and intervention phase. Lastly, in section 3.11, we draw conclusions and present suggestions for future works.

3.6. RELATED WORKS

Three decades of effort within the MR in the industrial setting have produced a variety of prototypes, conceptions, and assessments suggesting the benefits of adopting AR and VR as helpful environments [8]. Some of these benefits include knowledge support, inspection, and training. This chapter presents the applications and opportunities related to the use of augmented reality and virtual reality in the context of the manufacturing industry.

3.6.1. Virtual Reality as a Platform for the Development and Training of Augmented Reality:

Despite the fact that augmented reality technology has the potential to make industrial maintenance more efficient, this type of technology has not yet seen wide application in real-world applications [9][11]. The difficulties associated with the development of augmented reality can be classified as follows [12]:

- Authoring: Augmented content creation;
- Context awareness: Content adaptation to the environment;

- Interaction analysis: Advancement of the interaction between the user and the system.

Prototyping augmented reality (AR) solutions in a virtual reality (VR) environment is one method to address interaction analysis. Here, variables such as field of view and image resolution can be adjusted in a safe and monitored environment [13]. In the context of fast prototyping of several concepts, Alce et al. [14] proposed the Immersive Virtual AR approach to develop a wearable AR interface, demonstrating its potential in an industrial environment. In addition, the existing framework for industrial product development can benefit from the use of virtual prototyping as it enables participatory engineering in open and dispersed environments that contain a variety of data and content formats [15]. It is not necessary to produce a substantial amount of content in order to create realistic virtual environments and data. This is because digitalization processes in the industry are accelerating (especially CAD models development and organized technical documentation). Therefore, implementing VR in industrial development processes can actually reduce production time and costs while improving the quality of interventions [15] without requiring additional tasks or the use of new resources.

The industry benefits greatly from VR training because of its high degree of customization and flexibility [6] and the possibility of providing standardized training across the globe for a range of skill levels using an unified device. Virtual reality also allows users to train realistically without having to physically go to the training site. For example, Borsci et al. [16] discovered that trainees significantly improved their learning of procedural skills when training in a virtual environment (VE), but there was no significant distinction between a highly immersive CAVE system and a more straightforward holographic 3D table. On the other hand, research by Gavish et al [6] found that conventional training methods and virtual reality training did not differ significantly in terms of performance. They caution that the results are based on a limited sample size and imply that VR training could continue to be beneficial. Overall, there is currently a lack of expertise on how fully immersive training environments should be designed to maximize knowledge.

3.6.2. Variety of virtual reality applications in maintenance

Yaiza Vélaz et al.[17] employed VR systems to train industrial assembly operations and investigated the impact of the interaction technology on the learning process. They deployed four different devices to train with the VR system on the assembly task (mouse-based, Phantom OmniVR haptic, MMocap3D and MMocap2D). A methodology for creating a virtual simulation scenario and virtual maintenance process for nuclear power plant in-service maintenance was proposed by Kuang Weijun et al.[18]. They illustrate how virtual reality technology can be used to improve the tested method of designing and verifying an in-service maintenance process for nuclear plants. Nirit Gavish et al. [6] provide yet another case research study in this field. Within the framework of the SKILLS Integrated Project, they investigated the application of virtual reality (VR) and augmented reality (AR) platforms. In a task involving the assembly of electronic actuators, they divided the VR system into training groups. They conducted an empirical analysis of the effectiveness and efficiency of VR system training compared to more conventional training techniques following the use of VR system training. Ding Zhou et al. [19] proposed an approach to estimating the maintenance time required for complex product systems using a virtual maintenance process simulation. They provided a method for estimating the time required for complicated product system maintenance using a simulation of the maintenance operations in virtual reality. Virtual Reality (VR) technology can be used to visualize electric power systems, and VR can improve the efficiency of vocational training. Virtual reality (VR) and 3D visualization techniques were used by Bartlomiej Arendarski et al.[20] to provides a knowledge about the maintenance of complex devices in electrical power systems. According to Franck Ganier et al. in [21], virtual reality technology presents innovative options for operator training in difficult tasks. Compared to conventional training, it is less expensive and has less restrictions. Transferring knowledge acquired in a virtual context to a real-world setting is the ultimate objective of virtual training. They looked at whether or not a maintenance method could be learned just as effectively in a virtual environment as it could in a classic training environment.

Not to mention the fact that many businesses have adopted this technology in place of more conventional methods of instruction. EON Reality [22] uses virtual reality technology in order to validate inspections and maintenance for preflight. As a result Operators benefit from increased capacity for learning, memory, and decision-making. Pixogroup [23]has used virtual reality (VR) technology to instruct its operators on how to change water filters. Everyone can study at their own rhythm, in a risk-free, efficient manner, through self-training. A multi-user training approach was also developed by Pixogroup using VR technology. Employees from different locations can collaborate in the same virtual workspace. Employers can observe and analyze trainees' abilities and practices in real time using the virtual reality training approach. The company can now better understand how each person operates and what kinds of risks they pose on the workplace to improve safety in the future.

All of these research studies point to the potential for using virtual reality (VR) in training, making it easier to comprehend and learn with the appropriate tools. Indeed, the intended impact to develop the training session content is not mentioned in the existing literature. The successful implementation of VR in maintenance relies on several factors, one of which is making VR content and behavior creation easier.

Most of the abovementioned virtual reality technologies rely on the assistance of shop floor personnel in associated production environments using expensive techniques. Despite their considerable importance, they do not provide a clear procedure for detailing the development of 3D models, the adaptation of those models to the environment, and the projection of the asset onto the application interface in a way that gives users a real experience. Given the current state of the art, we describe a VR/AR system that can be efficiently operated by operators to execute accelerated maintenance processes within their manufacturing unit. The suggested framework is intended to be a component of a comprehensive and interactive maintenance system that can reduce unplanned downtime and hence decrease mean time to repair (MTR) in production availability. Because of this, the application can be installed on head-mounted displays (HMDs) or simply on operators' handhelds, which is a key component of the concept of Industry 4.0. Our application is therefore a low-cost application that replaces paper-based maintenance instructions with virtual reality-based instructions.

3.7. SYSTEM APPLICATION CONTEXT

The mining industry is one of the main production poles in our world. This industry can be included in the perimeter of geophysical industries or chemical industries. It is an essential resource for many countries and a vast field for scientific studies and research. There is a need to understand waste management initiatives or to explore initiatives to minimize the waste generated by mining at the source level, in order to deal with any accidents or to protect the immediate environment and environmental components. The mining industry refers to all processes related to the extraction, management and processing of naturally occurring solid minerals from the earth's surface. Mining industries must improve their processes not only for the transportation and marketing of minerals to remain profitable and competitive, but also for extraction and processing, including all processes and operations for the production and maintenance of assets.

Drilling is a fundamental activity in mining, especially for the evaluation of potential and also for testing the rooting of anomalies. In fact, our application is included in the scope of a mining drilling project. And more specifically a unit within the process that is responsible for pumping additives to ensure the drilling process. The project adopts a vision of digitizing the different operations in different perspectives and operational parts. Here we are talking about the control, automation and electromechanical part.

The choice of the application part of our system has been made by analyzing the criticality and the role of each part of the drilling process. On the other hand, the analysis was done on the different subsystems of each part of the process. The pumping part gathers a classical equipment architecture with a documentation (manuals, operating procedures...) easy to master. A functional decomposition was made on the working perimeter for a total assurance of the choice of the elements for our application. On the other hand, the pumping unit is very essential for the assurance of a continuous drilling process without the risk of unplanned breakdowns of the drilling rig.

Surface drilling requires the use of a drilling fluid whose composition is configured to meet the geological conditions required according to the drilling depth. The drilling fluid also participates in the lubrication, the cooling of the drill bit and even the mechanical drive in the case of a drill bit. The drilling fluid, commonly called drilling mud, is obtained from a mixture of water and additives to obtain a higher viscosity of the drilling fluid. This essential step in the process is carried out by the pumping unit, which is why it was chosen for our application.

The cycle of the different circulating fluids is shown in the Figure. Each material transformer (subsystem) has an input and an output of different shape (material).

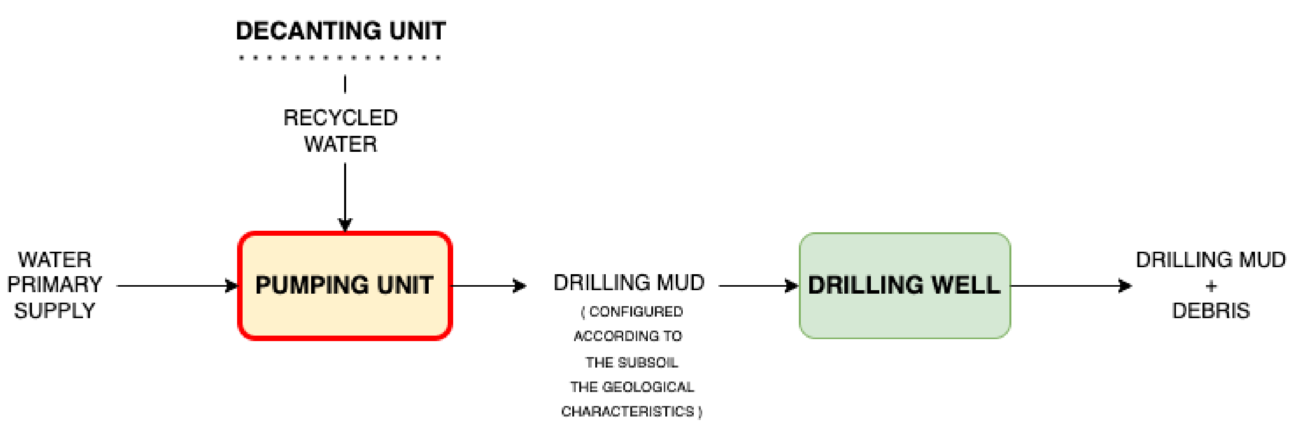

Figure 29: Pumping unit general process

The pumping process has two roles, first the generation of the drilling fluid configured according to the underground geological configuration and then the pressurization of the prepared fluid to the drilling rig and thus to the wellbore.

The pumping unit has two inputs and one output, except for the drainage outputs. The pumping system has two sources of fluids, a source of unaltered primary water and a source of recycled water from the decanting unit. When a given volume of water is acquired by the pumping machine, it is modified to meet the parameters programmed by the operator in charge or by the controller in the case of autonomous operation. Finally, the preparations ready to be pumped are pressurized to be conveyed to the drill pipe.

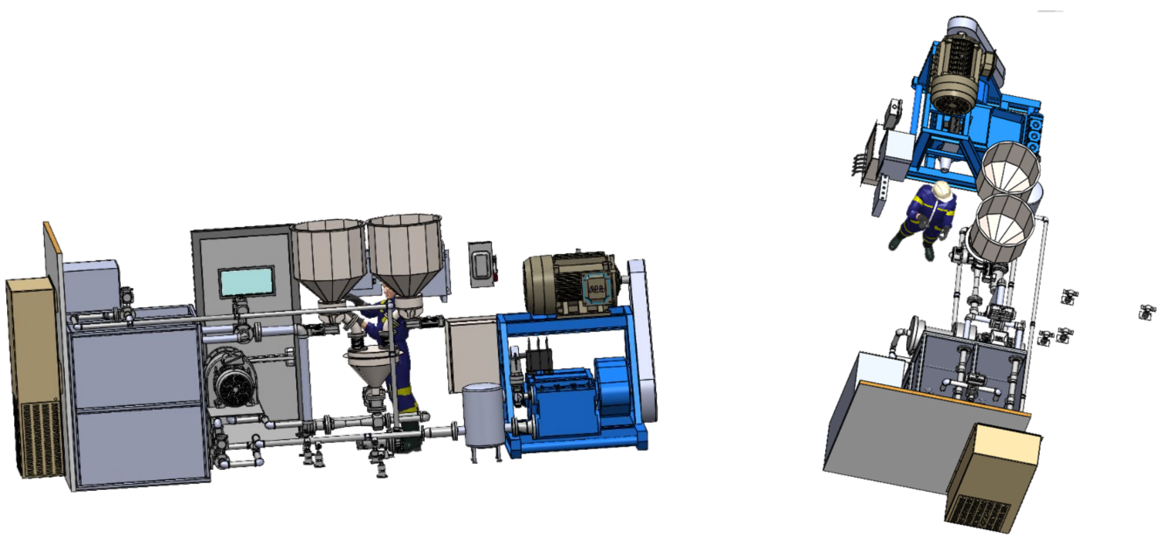

Figure 30: Pumping unit 3D-model

The pumping unit is composed of several components ensuring the whole process. For our study a functional decomposition was made on this unit by extracting the main components. Basically, we find a triplex pump with 150 HP motor, a pressure line, valves, decimeters, viscosimeters, densimeters, a shear pump and a 50HP motor. The set (Triplex pump / 150HP motor) ensures the control of the flow of the pressure line of additives. This triplex pump, equipped with the 150HP motor, is a class of slurry pump commonly used for oil drilling. The primary purpose of a mud pump is to circulate mud, also known as drilling fluid, during drilling operations. It works by forcing the drilling fluid down the hollow pipe string and up through the annulus. Indeed, for the remainder of this paper our application study is focused on this motor.

Tableau 3: 150HP Motor caracteristics

Moteur 150 HP						
Location	**Power (HP)**	**Voltage**	**Nominal current**	**Percentage for wiring**	**percentage for circuit breaker**	**Power (kVA)**
Triplex Pump	150	480	180	200%	250%	149,6

3.8. System description and methodology

3.8.1. System description

After the creation of the virtual environment of the drilling platform, a next step of integration of augmented reality in the same environment has been developed. This is the implementation of a maintenance management tool based on augmented and virtual reality.

The robust and particular working conditions in such a field of mining industry in general have pushed the development team of the tool to think of a way to eliminate all the risks related to maintenance operations. Here, we are talking about several circumstances that could affect the health and safety of the site maintainers. The dust, the noise level and the considerable risk of injury are all additional reasons to continue the development of the tool.

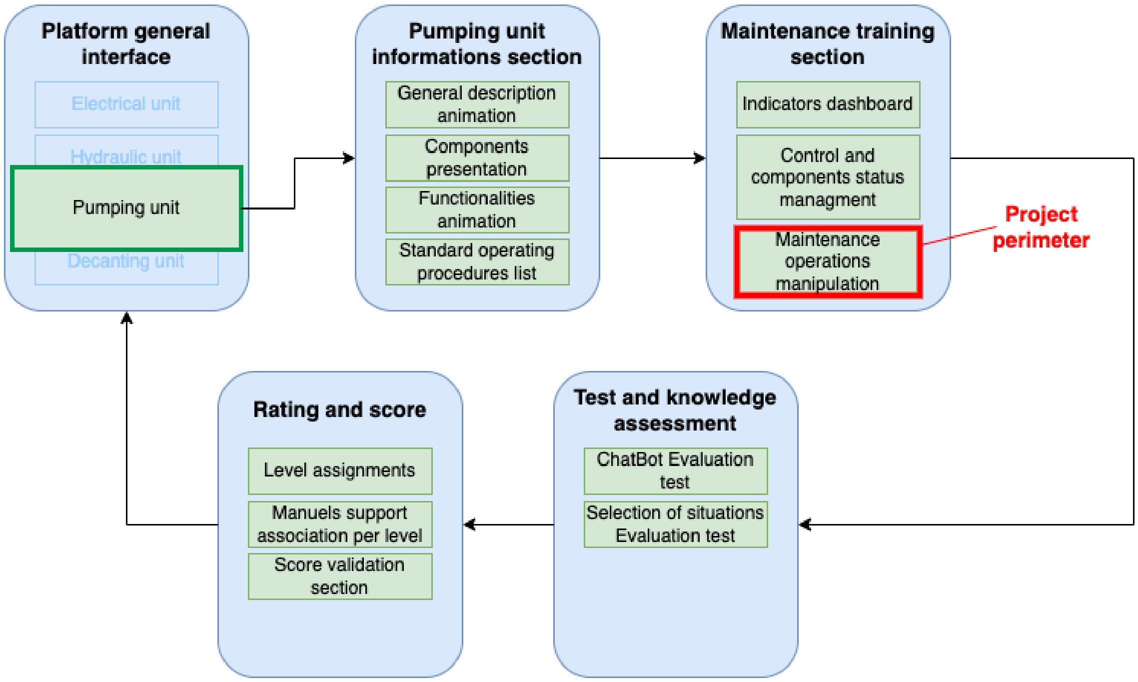

Figure 31: Application global flowchart

As already mentioned, our application project is multi-faceted. It is an application that digitizes the maintenance operations in our project area. Several perspectives have been adopted for the creation of the architecture starting with the theoretical and informative general component, passing by the practical component and arriving at the component of test and evaluation of knowledge.

The Application is a base for the different operators of the project with different levels of expertise. For this purpose, we have designed a looping Application architecture in order to scan the different stages of the project units. We built the VR Environment of the whole platform to prepare the interfaces. On the other hand, and as mentioned in the figure above, this paper will focus on the design, simulation and implementation part of a maintenance operation handling environment for the project pumping unit.

Figure 32: Platform Virtual environment

As a preliminary scenario, the user of the Application in our case will select the exploration of the pumping unit to learn more details. This selection will lead to a list of choices describing the different essential information to know about this unit. This includes a general description animated to illustrate the process, a list of SOPs, an animation of the features and a presentation of the components of the unit by animating the CAD of the equipment. For each selected component, the user will have access to its maintenance training section. The first one will present a dashboard of maintenance indicators (MTTR, MTBF, TRS, TRG...) this part will help the user to make an analysis of the indicators to be used at the level of the various methods of maintenance management. The second section will be dedicated to a presentation of component states (e.g. temperature, oil, lubrication, vibration etc.). The third section will be the subject of this paper. It is an environment for handling maintenance operations that will simulate the interventions based on the SOPs already presented in the previous section. A VR workshop has been created to fill this need. This workshop will give the user the possibility to manipulate the intervention with the dedicated tools while avoiding any safety risk. This application will help to go beyond the classical training framework based on paper manuals by giving different users (with different levels of expertise) the opportunity to use it as a basic support to master the operations. Once this section is finished, a test section will evaluate the knowledge acquired in the previous section. The user will choose two ways of testing, either in chatbot by answering direct questions, or by choosing the right animated situations as answer. As a result, each test will give a score to the user for his experience. This score will be associated with a level of mastery, knowing that for each level manuals are proposed to improve permanently the acquired skills.

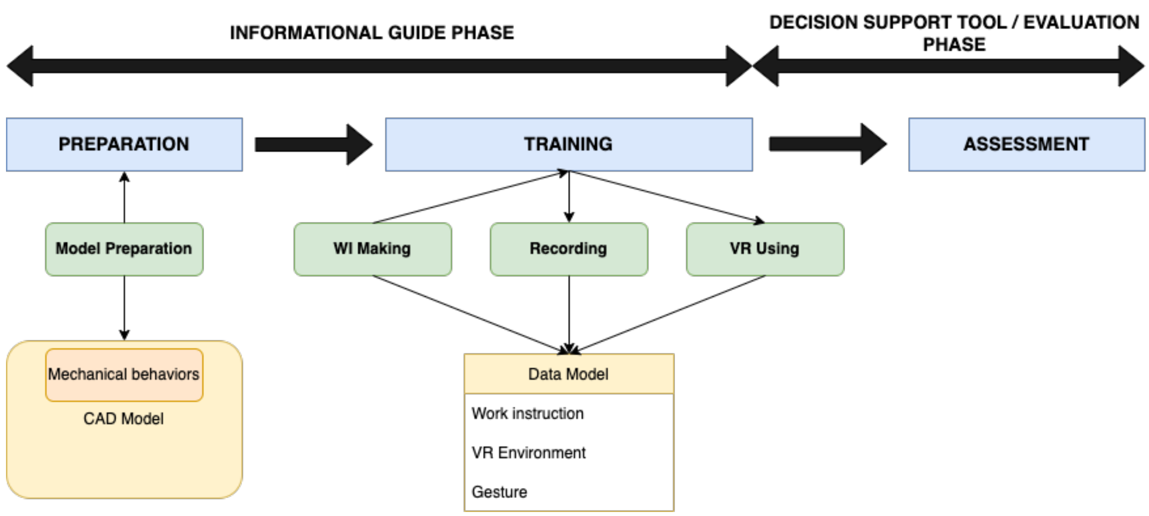

Figure 33: Our approach of the global virtual reality training application

In order to complement the training procedure for maintenance operations, we developed a concept that utilizes the virtual reality technology. When it comes to the standard training procedure, numerous companies opt for training their operators with the actual equipment rather than with a physical mock-up because the former is simpler to organize and more accurately simulates actual practice. Still, the actual equipment and the tools to use it are often difficult to obtain. Additionally, where serious safety concerns are present, training on the actual system should be avoided. Since we assume that VR technology can also assist in the setup of the training process for maintenance operations, the stage in which we are most concerned is the one in which the training plan is being prepared.

The three tasks that constitute our Virtual Reality Training Preparation Process are as follows: Preparation, Training execution and assessment, clustered in two phases, the informational guide phase and the evaluation phase. While most state-of-the-art articles evaluate the training phase, we focus on the preparation and training phase in this paper. In this article, we provide a comprehensive method for training. The Preparation task consists principally of 1 module (Model preparation), while the training task consists of 3 modules (WI making, Recording, VR Using).

3.8.1.1.Preparation task

The preparation task consists of a single element (model preparation). It is the basis on which the CAD model, the mechanical behavior and the documentation of the procedure are built. The model data is entered into the environment in this task as well.

- **Model preparation:**

In order to characterize the mechanical behavior of a part in the maintenance content and the CAD model (3D model), the model preparation module is utilized. In addition, the interaction between each component in the context of maintenance is described in this module. To import the 3D models into the VR environment, we first produced the 3D models using Solidworks software, and then exported these 3D files to the VR environment using OBJ or FBX formats, or any other standard.

3.8.1.2.Training task

The informational guide phase includes the training task as one of its components as well. It is necessary in order to operate the virtual reality application. The task is divided into three different modules: WI making, recording, and VR using.

- **WI making:**

The Work Instruction (WI) module explains the steps required to perform the maintenance work in the proper order.

- **VR using:**

Connecting to the VR application and devices can be accomplished through the VR Using module. The user is able to engage with the virtual reality setting on the VR application, and they can take advantage of the immersive experience through those devices.

- **Recording:**

The recording module is what's utilized to record the data that comes from the virtual reality environment, such as the posture, gesture, and position of the user, as well as the operation time. Position and motions are captured as 3D animations that can be played back at any moment. The virtual reality app lets users watch themselves perform maintenance tasks. While performing regular maintenance, the user's operating time is monitored.

3.8.2. Methodology

Unity is an open-source, multi-platform game engine that enables the development of interactive 3D content using a wide variety of its own integrated features. As already mentioned, our system keeps an exact position for each of the assets in the virtual workshop according to the deployed layout, so it displays the 3D CAD model of the engine at the beginning of the maintenance procedure to allow the user to navigate through the proposed maintenance steps.

For the architecture of our methodology, the opening of the application and the interface aimed for the handling part of the maintenance operations ensures the choice of the path described in Figure 03. In our case the choice of the component of the pumping unit is required in this case we speak of the Engine 150HP. It is essential to mention that for each choice of component the tools, the component and the spare parts change and this at the level of the tables dedicated to this purpose. The choice of the engine component transfers the user to our environment illustrated in the following sections. Thereafter the import of the CADs is carried out by the UNITY engine. As described in figure 05 "Model preparation unit" ensures the control of the behavior and mechanical movement of the different 3D components imported in our scene or environment. The WI then ensures the transmission of the manipulation declared by the user through the dedicated device. For the application in this paper, an assembly and disassembly command is offered to the user. After the validation of the Action by the user, each detected frame is checked by the Algorithm integrated in the software. This is an instantaneous correction that ensures the adaptation of the user's position to the position of the assets. The choice of assembly or disassembly is followed by the activation of the steps in full compliance with the procedure set at the top of the Asset (Engine 150HP). For each step, the tool is selected for manipulation and vice versa for each step. After the validation of each step the transmission would be automatically for the following step. This validation is illustrated afterwards by an animation of each step. If finally, the operation is validated by the operator the maintenance loop is finished otherwise the loop is restarted. After the end of the loop the user will go back to the general interface.

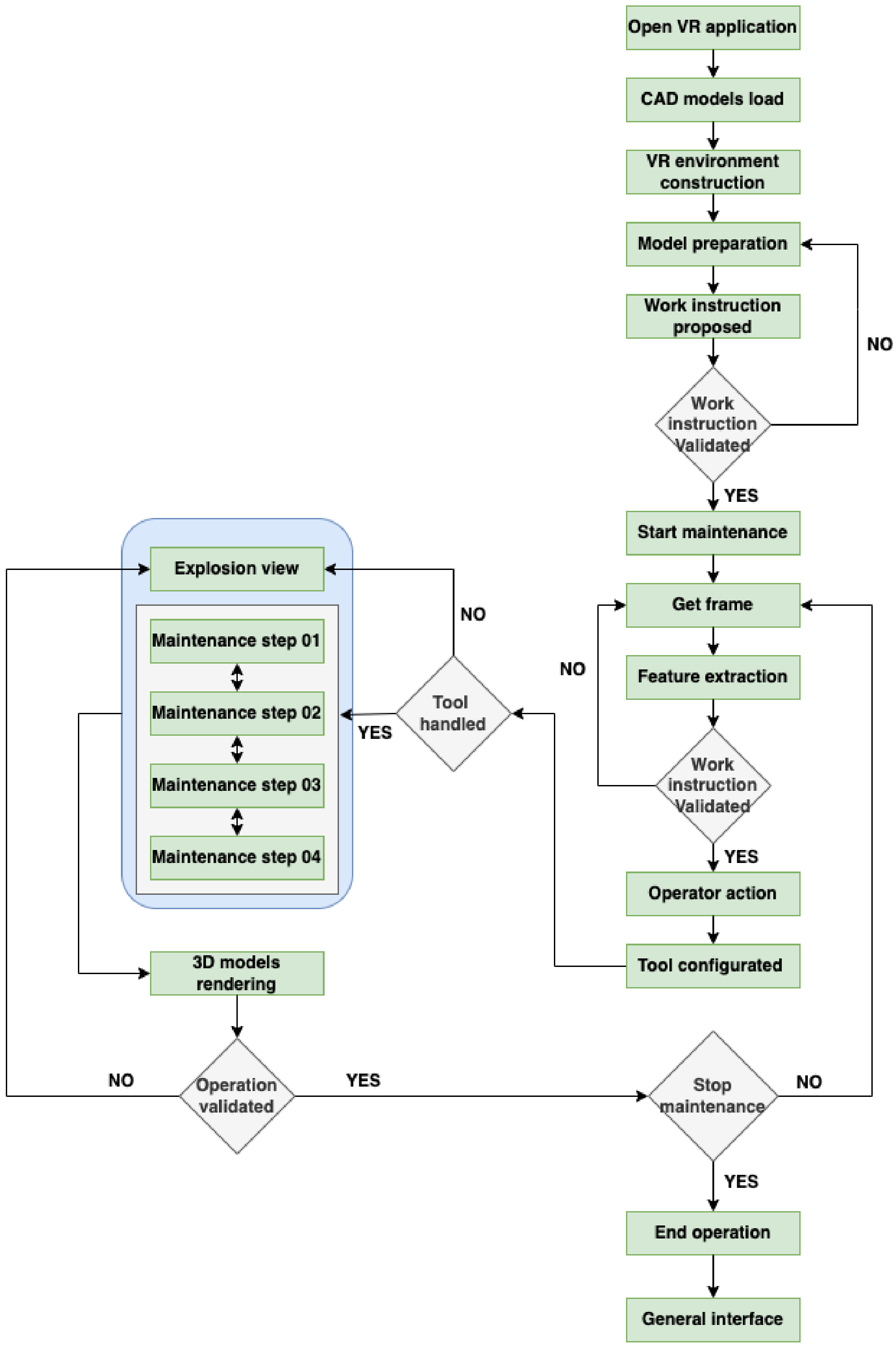

Figure 34: Flowchart of the proposed methodology for the virtual reality system for maintenance training operations

3.8.2.1. 3D Model design philosophy

During maintenance operations, 3D objects are used to provide an overview of the relevant steps of the maintenance task in a clear and understandable way. Before starting the process of creating a 3D object, it is essential to identify the limitations of use and the resolution of the drawings required. Models rarely require detailed, high-quality drawings. In addition, in this paper we have optimized the size of the 3D files used for maximum use of the components by ensuring optimal quality to the user. The number of polygons, animations, materials and textures that give the user an impression of realism all contribute to the overall file size. This is true regardless of the type of program used. For our system, one of the most important considerations for 3D object production is whether it is capable of running smoothly on the vast majority of mobile devices while requiring an appropriate level of processing power.

3.8.2.2.3D Modeling of the maintenance unit and related specifications

During the process of creating a 3D model of the maintenance unit (as shown in Figure 7), the information contained in the model (name, size, unit, coordinates, material...) must be consistent with the actual production specifications. This facilitates the programming of the model and software between import and export. Figure 4 provides a visual representation of the phases involved in the system development process for our virtual workshop.

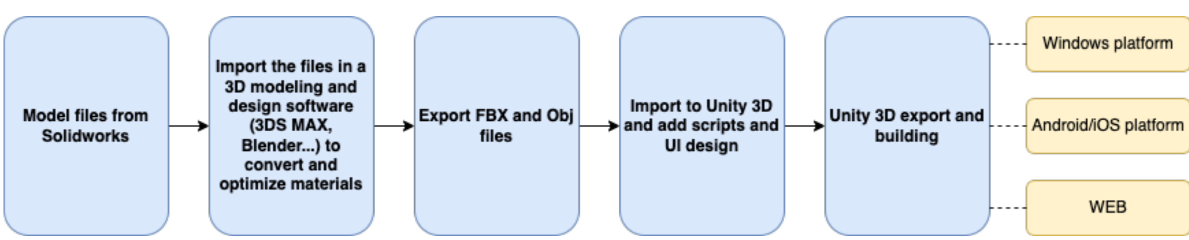

Figure 35: System development process

3.8.2.3.User interface

The use of head-mounted displays, virtual reality glasses, smartphones, tablets and personal computers are all valid options for accomplishing the task of visualizing the maintenance procedure. Since the vast majority of our engineers already own smartphones capable of running the application, and since virtual reality headsets are becoming increasingly affordable, we have adopted a BYOD (bring your own device) policy. Concerning virtual reality glasses, owners of smartphones already have the knowledge necessary to operate them.

The interface that is being provided has been developed in such a way that it can answer to any and all requests that may be made by a user of the Application. The simulation and animation of the maintenance method can be accomplished with the help of a few different commands. The various commands that can be used with our program are compiled into a general interface. One command is used to launch the virtual environment, another to select the component, a fourth to access the user manuals and other documentation, and the final command closes the user interface. Each command, based on the architecture, leads to a certain set of operations. The opening command provides the opportunity to incorporate the workshop setting by presenting two more action options, which are, respectively, assembly and disassembly. Each of these actions has a specific context that the user must keep in mind at all times. The engine can be seen in its entirety during assembly, but during disassembly, it appears in a fragmented state at the beginning of the process. The user always returns back to the SOP panel while working through each procedure, which allows them to keep an eye on the animations that are being shown in the workshop. In addition, Unity 3D ensures that 3D assets are imported into the virtual environment with all actions and commands that need to be deployed. From the last step to the first, the operator can learn the assembly/disassembly procedure. Furthermore, the available explosion button elegantly separates the motor's various elements and components, assisting operators in comprehending the motor's structure.

3.9. TOOLS

This section provides a quick overview of the resources used in the development of the suggested Virtual Reality approach. Specifically, we detail the layout of the workshop, the 3D modelling software, the software used to prepare the virtual environment, the devices that can be used after the application has been built.

3.9.1. Maintenance unit layout

Recent studies highlight and discuss the importance of layout design in comparison to concerns regarding safety. When it comes to maximizing the effectiveness of the primary production line, the layout design plays a significant influence. In addition, the prior research only looked at conventional indicators like the amount of time spent in the system, the amount of time spent waiting, the availability of machines, the length of queues, and the amount of time operators spent working.

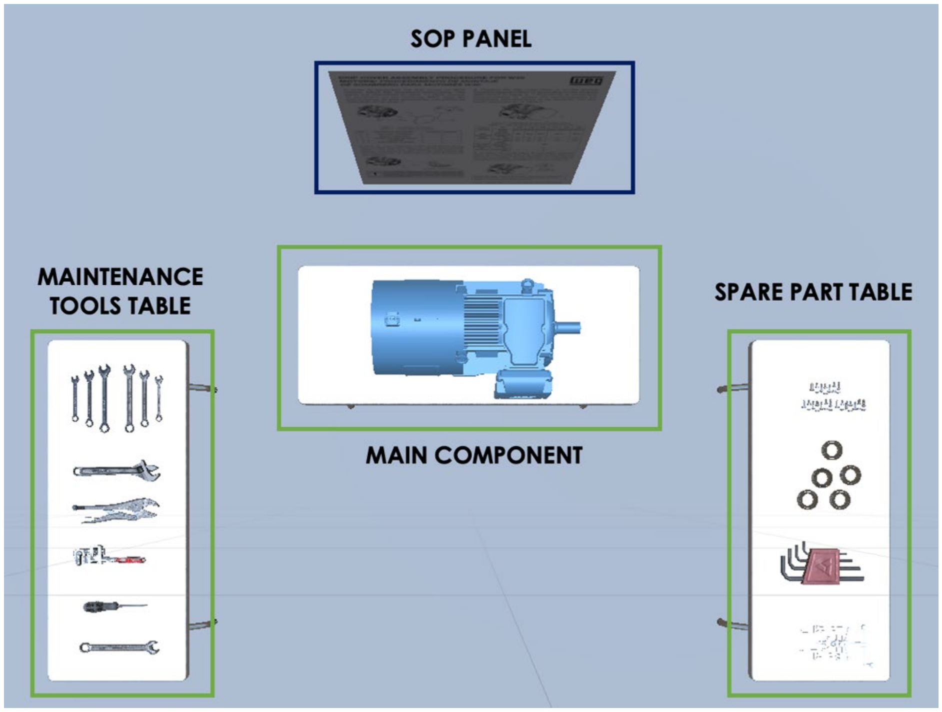

Figure 36: Layout of the proposed maintenance unit (Top-view)

Regarding the layout, after conducting research into the various kinds of layouts, we decided that the layout U was the best option. [24] has conducted research into the maintenance units with regard to the form and characteristics of the layout. The findings of this study demonstrate that this particular form is both efficient and flexible, making it suitable for more optimal operations that have an effect on the amount of time and resources required for subsequent interventions. Due to all of these factors, we have decided to take this approach by incorporating the operational procedures panel as a means of providing assistance to users.

3.9.2. 3D Modeling and software

In the process of creating a virtual environment, the first type of virtual reality modeling method is 3D graphics based and uses computer graphics technology to model and render a virtual environment. The second type of virtual reality modeling method is image-based and uses multiple viewpoints, panoramic views, or images taken in any direction to create a virtual environment [25]. Computer graphics-based methods are highly interactive, although in some cases they place heavy demands on hardware and software due to the complexity of the modeling and rendering process and the need to ensure a smooth experience in real time. When constructing a virtual reality system using this method, a sizable portion of the work consists of creating a realistic three-dimensional model. In the field of virtual reality, the initial stage, the foundation, and the core is 3D modelling. Other interactions will consist of silence if a good model is not present.

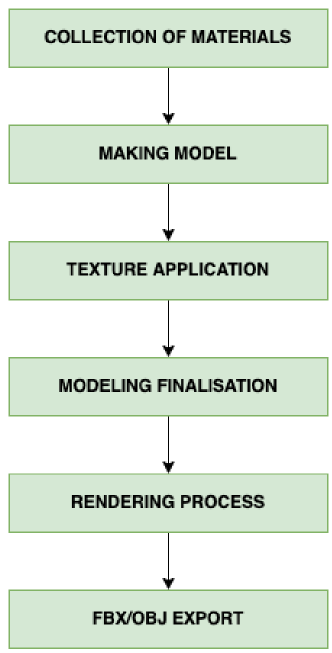

Figure 37: 3D Modeling Process adopted

In the context of our working environment, there are a number of components that must be present in order for our workshop to be considered fully functional. Each and every design is created using the Solidworks software developed by Dassault Systèmes. The designs were developed in such a way that they satisfy a number of criteria regarding measurement, quality, and realism in order to achieve a higher level of compatibility with the virtual environment. For our application, each maintenance operation involves tools, components, as well as spare parts, and the nature of the intervention and the nature of the asset that has to be maintained or repaired determines how these three things must be updated. When it comes to the assembly and disassembly of the engine in question, a list of the necessary tools has been prepared by consulting the relevant manuals and maintenance instructions. After preparing the tools we designed the spare parts for the same intervention and then a realistic design of the 150HP WEG engine (Figure10). Since the version of SolidWorks that was used to do the mechanical design does not give the option to export fbx or obj files, the files that were exported were in the LDPRT format. as shown in figure 07, we needed to make use of two more of software, namely 3DS MAX and Blender, in order to complete the final adjustments on the assets. These finishing touches included the optimization of the file sizes, the adding of the appropriate textures, and the subsequent export of the files as either Fbx or Obj. The workshop consists of several other fixed and non-animated elements such as the tables and the procedure panel.

Figure 38: 3D CAD geometries of components for the virtual environment

3.9.3. Virtual reality environment deployment

Unity 3D, developed by Unity Technologies, is a powerful game engine. It works on multiple platforms and is scriptable in C#, allowing for the creation of both 2D and 3D animations. Among the most widely-used AR/VR engines, it supports human-computer interaction by providing development tools for mobile applications. Unity provides developers with pre-defined development functions that may be used to generate dynamic 3D material that can be applied in real-world settings. In addition to this, Unity guarantees that the created program may be exported in executable files that are compatible with the most common mobile operating systems, such as iOS and Android.

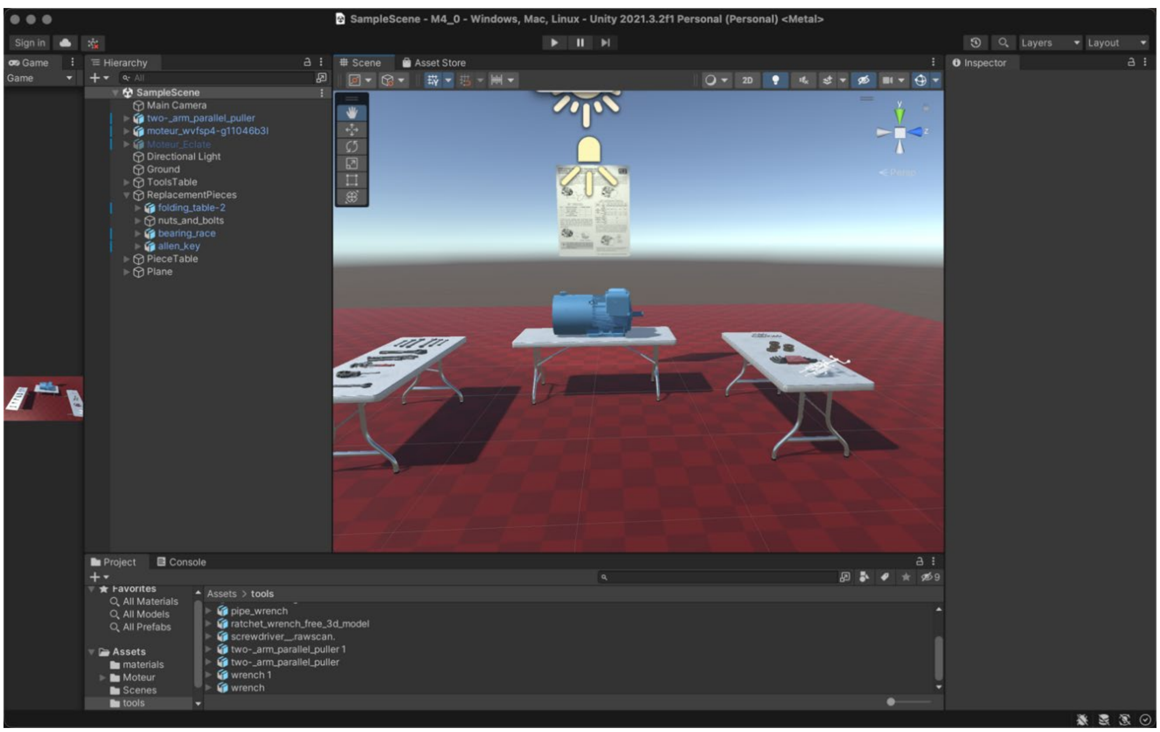

Figure 39: Unity 3D development interface

Establishing virtual work settings and producing three-dimensional models of each component of the workshop while maintaining a number of realistic qualities can be a challenging task. Since tools, spare parts, and engines are the primary objects of virtual maintenance (with specific sizes), the system places stringent requirements on the model of this component, which must be made from the equipment drawings [26]. On the other hand, as a non-mechanical professional virtual maintenance system, we are able to optimize the model in such a way that it doesn't take an excessive amount of system resources in order to promote it. This is predicated on the assumption that the model is capable of satisfying the principle needs of the application. Another development point is the interactive mode between the user and the virtual maintenance system. In order for the system to carry out the numerous commands that the user has issued to the model and, at the same time, to transmit back to the user the required information and changes in the model itself, the user must interact with the system in the virtual environment. This interaction allows the system to carry out the commands. By writing a program in Unity 3D, users are able to control the operations of moving the virtual scene, moving objects, disassembling, repairing, and maintaining components by using a Head-Mounted Display (HMD) or just a smartphone.

3.9.4. Proposed hardware devices

It is preferable to have a correct definition of the operational environment of virtual reality before attempting to handle it. The virtual reality operating environment can be thought of as a system, the primary purpose of which is to present a particular technical situation associated with an industrial unit. Integration of many different technologies and tools is required in order to facilitate a more fluid operational environment for 3D virtual reality. In order to create a smooth working environment for virtual reality, it is necessary that all the required hardware and tools are compatible with one another. This type of virtual reality environment is created by combining software and hardware technologies, which then enables the designer to become completely immersed in the scene. Through the utilization of a head-mounted display, this system provides the operational technician/engineer with graphics of an exceptionally high quality that are stereoscopic.

The essential movement of the head-mounted display is monitored and controlled by electromagnetic or camera-based orientation devices, which dynamically allow the operator to look around. This movement is required for the HMD to function properly. The user's hands, which are equipped with extra positing devices, are used for tracking and monitoring the various movements of their head. These motions are utilized in the process of developing and manipulating various operating scenarios within the virtual environment. An instrumented glove is worn by the user so that movement of the fingers and wrist can be tracked and evaluated. The operational team utilizes such a virtual working environment to decide on the best order in which to do operations, to assess the necessary limitations, to develop operational plans, and to visualize the consequences of those plans.

Integrating numerous disciplines and coordinating them with associated technology is crucial for the design and development of a virtual reality environment. The overall effectiveness and efficiency of the VR application improves with such integration. Technicians and engineers can now do operational tasks in a virtual setting thanks to the introduction of virtual reality. This virtual operational system facilitates applicable training instruction in a dependable simple way. Here, users can interact with a 3D virtual world in real time and experience its simulation.

Our policy of establishing the maintenance training system is based on two very essential factors for an efficient and economical implementation at the same time. As mentioned in the previous paragraphs, one of the objectives of our vision is to realize the BYOD (bring your own device) which remains a pillar of the industry 4.0 nowadays. Our application could use a smartphone as an economical means to be configured instantly. On the other hand, the use of an HMD virtual reality headset remains an investment that ensures a better experience and subsequently better results affecting production performance and maintenance indicators. For this reason, we propose to merge the two devices according to the need and the context of use (the space of implementation and the period of use). In terms of Building, Unity 3D ensures an operational application export for both devices. For this paper we propose to use an HTC Vive headset as a first test after the validation of the Workshop environment.

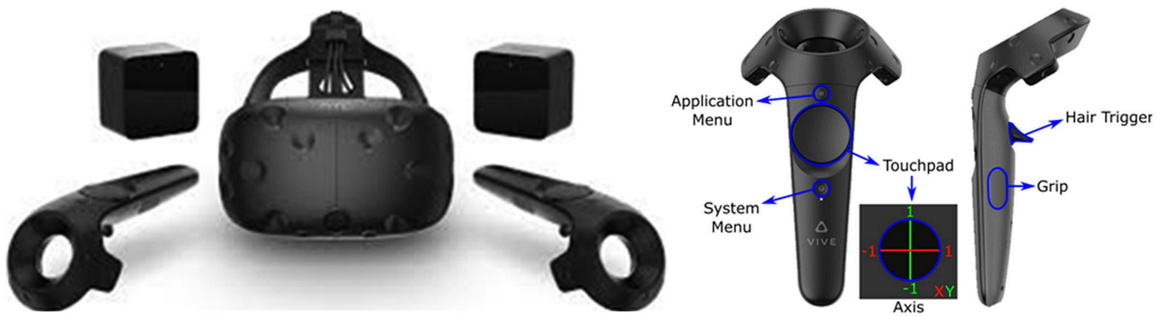

Figure 40: HTC Vive VR Headset

The HTC Vive is a virtual reality headset developed jointly by HTC and Valve. With the use of room-scale tracking technology, the user can freely navigate a virtual 3D environment. Figure 13 depicts the lighthouse base station required to set up and run a virtual reality session using the HTC Vive virtual reality headset. It uses a combination of a gyro sensor, an accelerometer, and a laser position sensor to determine where the user's head is in space. One display is placed in front of each eye, and a camera in the centre of the device provides an aerial perspective of the user's immediate surroundings. Users are able to wirelessly interact with virtual items using the HTC Vive controllers, which results in a more realistic experience for the user. These types of controllers are considered to be the hands of virtual reality. As can be seen in Figure 12, it incorporates a track pad, grip buttons, and a dual-stage trigger into its design . The Vive tracker is capable of performing functions identical to those of Vive controllers and the Vive headset by gathering data from the infrared radiation emitted by base stations. Using the tracker, the user will be immersed in the virtual reality environment.

The HTC Vive system uses two black boxes, or "lighthouses," to generate a 15-by-15-foot sphere of virtual reality. With the help of the 37 sensors built into the headset, this lighthouse tracking system keeps track of your every move with sub-millimeter accuracy. The base stations for an HTC Vive are shown in Figure 13.

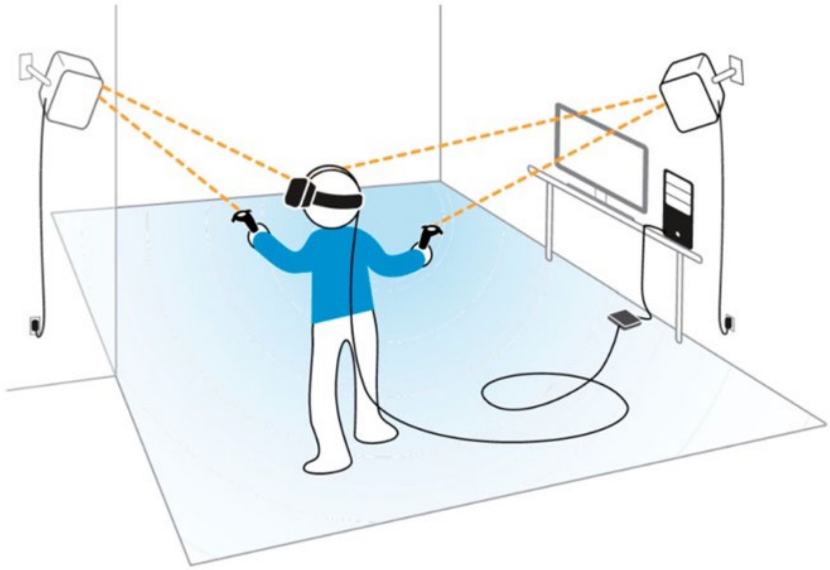

Figure 41: HTC Vive stations set up position

3.10. ENVIRONMENT IMPLIMENTATION

The operational scenario is built up in the generated virtual environment, and the proposed methodology makes use of a motor that is used in the pumping unit. For the current maintenance procedure to be carried out, it is necessary to have an operator who is capable of reading the detailed instructions from a paper book and carrying out all of the necessary steps. The users need to be shown a demonstration in real time of how the maintenance procedure works in combination with the shop floor environment. As an effect of this, we believe that the virtual reality preparation training approach can successfully replace the more conventional training method of using physical mock-ups. As a first step, the VR environment was made on the Unity program and simulated on a 2D computer for the engine repair.

3.10.1. Maintenance scenario setup

In the study of this paper, the asset studied is a motor, which is included in the set {Pump+Motor} ensuring the whole process of pumping the additives in the drilling procedure, as discussed in section 3. It generates the energy necessary to convey the various additives, regardless of the nature of the substances, their density, or the flow rate. Because of the nature of the operating environment as well as the circumstances of usage, it is necessary for us to attach a preventive maintenance plan to this asset in order to guarantee that it will be completely available at all times. As part of the process of maintaining the system, the maintainers are required to do regular replacements of the spare parts and a comprehensive inspection of the components. In order to perform the remaining phases of the plan, these two interventions will typically require an operation of disassembly followed by a later operation of assembly. We have therefore conducted research into these two procedures, detailing the positions of actions, the instruments employed, and the characteristics of placement.

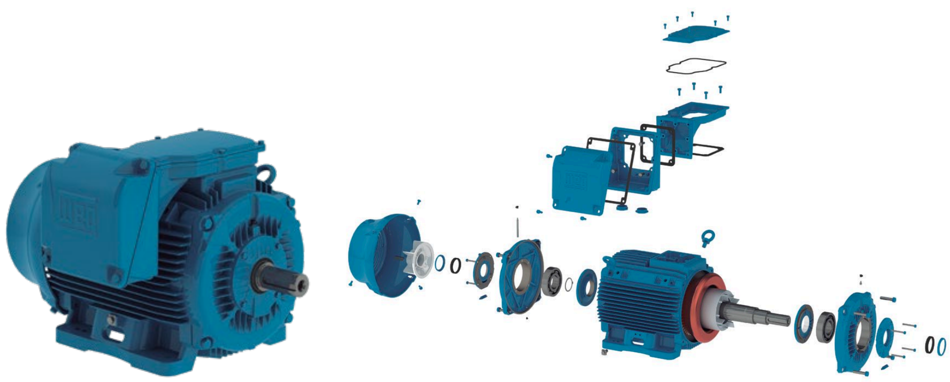

Figure 42: 3D exploded view of the Weg motor deployed for the application

The first step is to design the 3D CAD models needed to develop the specific maintenance scenario by referring to the actual models with model specifications and dimensions as discussed in Section 5.2. To support the above process using VR techniques, the compressor parts must be designed in 3D CAD models. To be more accurate, each part of the Engine Chassis Assembly is designed separately for clearer animation (Figure14). We leveraged our mechanical design experience with Solidworks software to design and finalize the CADs. Afterwards, the export of the elements is done in .obj or .fbx to integrate the environment on Unity 3D.

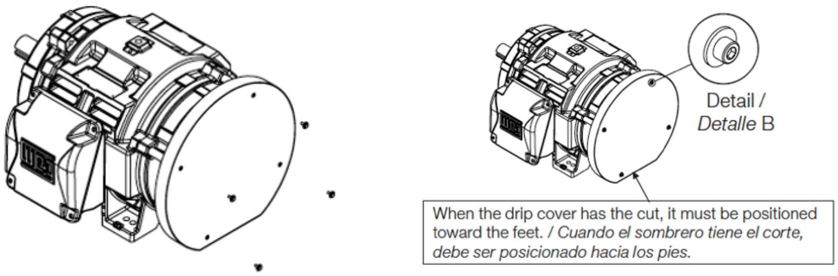

Figure 43: Paper-based technical drawing, presenting the assembly of the motor

In the scenario described in section 4.2, after the Assembly/Disassembly intervention is selected, a sequence of actions is specified, and these actions will be shown on the device used by the operator. To be more specific, the maintenance can be broken down into the following 5 stages:

- Phase 1: Tool selection;
- Phase 2: Scruers remove;
- Phase 3: Bolters remove;
- Phase 4: Newport fasteners remove;
- Phase 4: Animated disassembly after the removal of all bolters and parts;

The standard operating procedure on paper is used to provide a visual representation of the standard maintenance procedure. In addition, a portion of that procedure is shown in figure 15. In addition, this engine procedure includes step-by-step instructions above the engineering drawing. Therefore, during maintenance, a significant amount of time is spent understanding the instructions on paper, depending on the level of expertise of the operator [27]. The combination of the standard operating procedure and virtual reality is utilized by our solution to close the knowledge gap that exists between maintenance experts and less experienced operators.

3.10.2. Environment demonstration

To assist the user in navigating the disassembly process, the application chooses both a brief overview and the appropriate 3D object to match with each phase. At the beginning, the user chooses to start the maintenance, the environment prepares for the beginning of the already chosen intervention (assembly/disassembly), as well as several information about the following phases. Then, the application tries to locate the characteristics of the engine on the chassis, in order to visualize the first phase of disassembly. To complete phase 1, the user must unscrew and remove the five screws on the front phase and the 8 screws on the right and left phase (figure 16a). The next step involves removing the front phase in the corrected position (Figure 16b). After removing the outer surface of the front phase, the user is guided to unscrew the bolts of the upper phase (figure 16c). Finally, the application visualizes the removal of each screw of different nature (Machine screw, Thread cutting machine screw, Socket screw...). A confirmation animation at the end of the operation is deployed in the sender (Figure 16d). At the end of the operation, the user can navigate through the assembly tasks. At any time, the user can choose the explode option to dynamically inspect the correlation and assembly of different parts (Figure 16d).

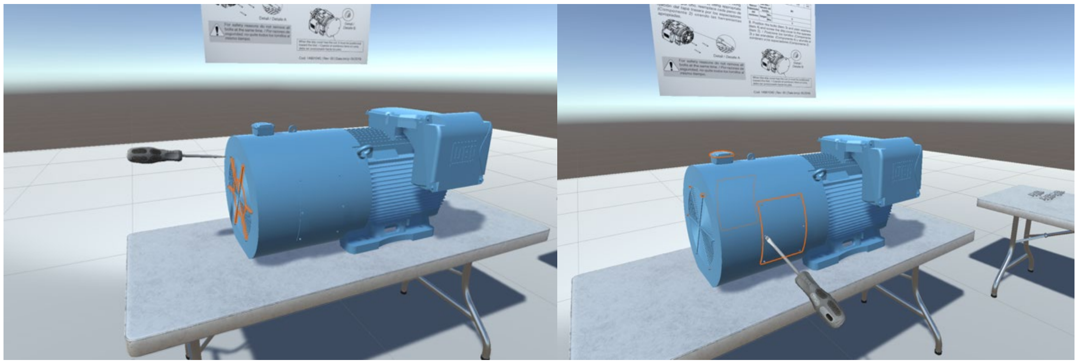

Figure 44: First phase (screws remove)

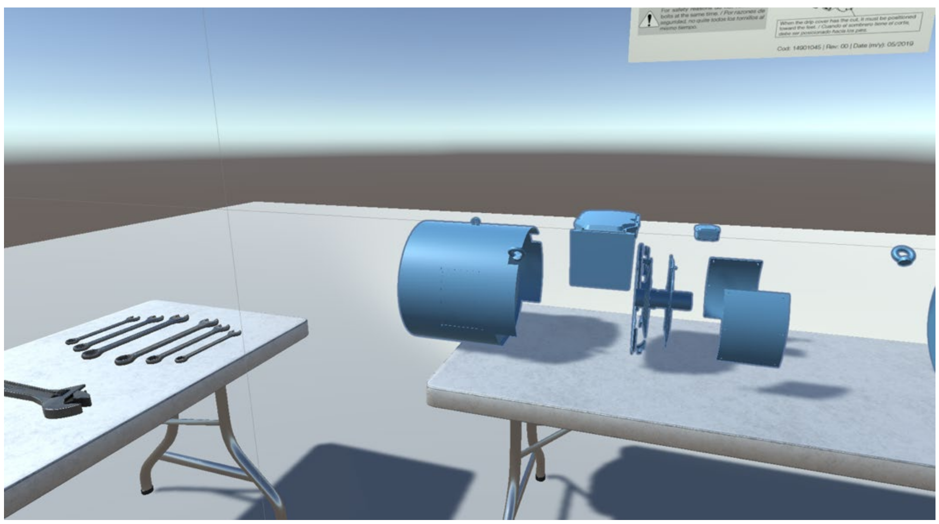

Figure 45: Front phase remove validation

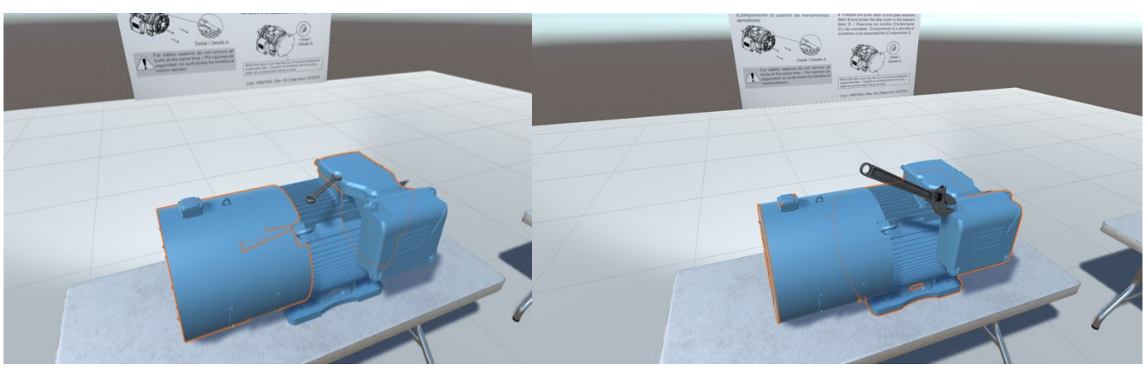

Figure 46: Upper phase bolts unscrew

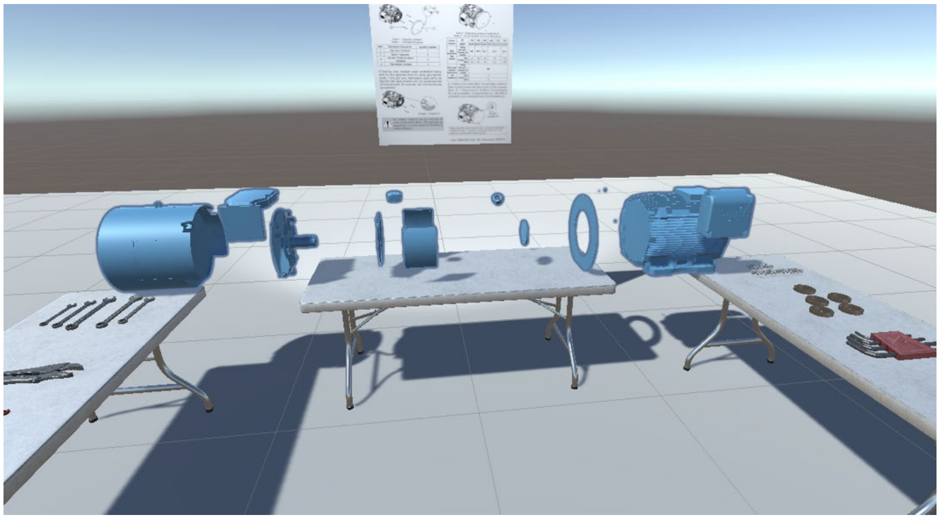

Figure 47: Disassembly final animation

During the disassembly process, the program chooses a brief overview and the appropriate 3D object to correlate with each phase in order to direct the user. The environment that has been built is a component of the larger project of digitizing the drilling unit at the Laboratory of Materials, Products, and Processes (LMP3), which brings together a group of specialists from a variety of sectors. Within the context of our project perimeter, the ultimate objective was to design an intelligent maintenance management architecture using the principles of Industry 4.0. This goal was our starting point when the project was initiated. The maintenance unit environment was given generally positive grades, which verified its contribution as a pillar that can successfully support maintenance engineers. This is due to the fact that the procedure can be carried out without the requirement for operators with a high level of expertise. The demonstration of the environment revealed that it has the ability to make complex maintenance operations easier to understand and perform. In addition, there was a clear interest in utilizing the program as a method for training inexperienced maintenance operators, which would reduce the amount of time needed for training as well as the total amount of time needed for repairs. In conclusion, the implementation of exponential digital technologies into medium-sized companies, such as the project described in this paper, has the potential to increase industrial competitiveness in the context of the global landscape.

The conceptual framework presented in this study has the potential to be implemented not only in manufacturing contexts, but also in totally unrelated fields, such as mental health [28], infrastructure [29], and education [30]. Our application framework, in general, expands the users' field of vision by providing information that is accessible in real time, which minimizes the amount of time needed to comprehend the processes. It is crucial to perform a cost-benefit analysis [31] in order to increase the adoption of our method across the complete production chain, which is the most essential component of the drilling unit. In the cost-benefit analysis of a computer-aided maintenance program, the frequency of failures, the cost of spare parts, the amount of time required to fix the machine, and the cost of external subcontractors per machine are all correlated. On the basis of the findings, the first machines to apply the basic structure of the Approach described in this paper will be determined, and this will ensure that the machines can be recoverable. On the basis of the findings, the first machines to apply the basic structure of the Approach described in this paper will be determined, and this will ensure that the machines can be recoverable. After that, a process that is analogous to the one that is described in Section 6.1 needs to be performed. The viability of the application is dependent on the possibility of unplanned maintenance procedures. This indicates that if the original equipment manufacturer (OEM) were to standardize the maintenance procedure, the identical scenario would operate correctly. In scenario in which this is not the case, the success of the procedure is dependent on the experience of the operator, who will be required to complete additional steps that were not planned. With 3D digital models readily available, even the intricacy of the maintenance method throughout deployment is a manageable effort. If the original equipment manufacturer (OEM) is able to supply the 3D models, or if the manufacturer already possesses the digital data, then the amount of time necessary for their implementation is considerably less than if they were designed from zero. Our method eliminates the knowledge gap between original equipment manufacturers (OEMs) and maintenance operators by providing specifics on the construction and application of pipelines. The system is clearly designed so that repair procedures can be accelerated without affecting quality, and it can be linked to a more comprehensive maintenance system to minimize mean time between repairs (MTTR) and increase production availability.

3.11. CONCLUSION AND FUTURE WORKS

Within the framework of this article, we define the idea of a Virtual Reality (VR) Environment that can serve as a platform for the planning and executing of VR maintenance capturing and training sessions. This research is the first step in the process of developing a methodology for designing and creating work instruction using virtual reality technology. Our virtual reality environment will make use of the identification of the right virtual reality tools and technique in order to provide the capacity to train maintenance operators. In addition, we are going to request the participation of maintenance specialists in order to test and replicate the work instruction within the virtual reality setting. The model's operating instructions can be recycled for use in maintenance training in a variety of formats, varying from the conventional paper instruction to the highly complex VR training modules, with an easy-to-follow video preparation possibility also. The most important benefit is the capability of performing precise gestures, which is explained by the fact that occlusion problems are reduced.

As part of our ongoing work, we will have to determine which hardware tool or system will be most suitable for the task at hand, as well as how it might be implemented in order to create and assess the real training procedure that is associated with the maintenance task. We developed a list of open questions regarding devices and platforms. Additionally, we will investigate alternative VR tracking systems and devices, focusing on those that are capable of tracking both the hands and the body. In this regard, we are in the process of evaluating the building of our program on the HTC Vive, as described in section 5.4, as well as preparing the environment for export to the iOS and Android operating systems. Because the quality of the tracking is dependent on the hardware, one of our goals is to explore which tools and hardware are the most appropriate and efficient for specific training creation operations based on our methodology.

We plan on integrating touch-based devices and adapted interfaces into the training environment in order to provide the user with improved direction while performing the training tasks. We intend to increase the level of VR immersion by enhancing the material as well as the virtual environments that are designed to be as similar as possible to the actual work.

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CONCLUSION GÉNÉRALE

Pour améliorer les techniques de maintenance intelligente, cette recherche propose de nouvelles approches combinant l'intégration des technologies tout en gardant le lien avec l'industrie 4.0. En ce sens, des études approfondis ont été faites concernant les différentes outils de la maintenance intelligente, et l'efficacité d'une intégration des technologies de tendance comme la réalité augmentée et la réalité virtuelle dans le même cadre d'opération. Pour y arriver, le premier objectif était principalement focalisé sur l'exploration des différentes applications d'intégration de la RA les opérations de maintenance. Il était question de mettre en évidence les avancements et les travaux effectués dans ce domaine. Cette première étape avait pour but d'avoir une idée claire des directions que nos études et nos recherches peuvent prendre. Le second objectif était destiné à proposer une approche d'implémentation de la RA dans les opérations de maintenance à distance (télémaintenance). Pour cela il était important de concevoir une structure claire en commençant de l'élaboration de l'architecture globale en arrivant au cadre d'interface d'utilisateur proposé. Pour nous, il est essentiel de proposer ce cadre théorique comme approche pour faciliter toute implémentation concrète future en utilisant les mêmes piliers adoptés. L'objectif était de l'exploitation de tous les outils d'instauration en suivant la tendance et les avancements actuels. Le troisième objectif visait à étudier la bonne approche de conception d'un environnement de formation des opérations de maintenance dans le cadre de la réalité virtuelle. Le travail avait pour but la description d'une méthodologie complète en utilisant les moyens adaptés en termes de logiciels et matériel. Pour atteindre tous ces objectifs, l'étude a été divisé en trois phases dont chacune avait pour vision de faire avancer la recherche, pour accéder aux buts fixés liés aux problématiques. Les deux technologies (la RA et la RV) ont été exploités pour faire en sorte que notre étude touche en perspective extensive les opérations de maintenance en termes de volet formatif et celui de mise en place des interventions en scénario réel.

La première phase de cette étude avait pour but de regrouper tous les travaux précédents et les applications développées dans le domaine de la réalité augmentée et la maintenance intelligente 4.0 sous forme d'une revue de littérature. Dans cette partie de mémoire, les différents outils de maintenance intelligente sont présentés. Les applications de réalité augmentée dans le même domaine sont aussi présentes dans ce premier chapitre. Les piliers de cette technologie font partis de cette recherche. En effet, on peut trouver des parties dédiées aux différentes nature d'interventions mis en terrain en exploitant la RA. Ce papier était une phase essentielle dans notre travail de recherche car elle nous a permis de mieux diriger nos travaux et avoir une idée des améliorations futures que l'on peut développer.

La seconde phase de l'étude avait pour but de bien décrire et concevoir une approche d'implémentation de la RA en exploitant toutes les informations et avancements mentionnées sur le premier travail soit en termes de maintenance ou en technologie elle-même. Dans cette partie de mémoire une description totale et détaillés a été faite pour une bonne compréhension des étapes de mise en place de la technologie pour les opérations de maintenance. Un point très essentiel a été ajouté comme particularité pour ce travail : la télémaintenance. Pour concrétiser le point, et après avoir décrire la structure et les outils, une structure de communication a été présentés. Cette partie du chapitre avait pour but de détailler la solution qu'on propose pour assurer la bonne voie de communication entre le département de maintenance et ingénierie d'une part et les opérateurs de terrain de l'autre côté. Cette étude a permis de mettre en place un plan d'instauration complet, selon notre vision, en prenant en considération les différentes circonstances ainsi élaborer par la suite une interface d'utilisateur répondant aux besoins fréquents des deux parties en termes de nature d'opération ou des outils demandés et vice-versa.

La dernière phase de cette étude se focalise sur la conception d'un environnement de formation d'atelier de maintenance dans le contexte du secteur minier. Plusieurs motivations nous ont poussé à mettre en réalité ce travail vu les conditions et les circonstances d'un tel domaine ainsi l'assurance du volet de santé et sécurité du personnel de maintenance. Dans cette partie de mémoire, on a étudié la faisabilité de la mise en œuvre d'une telle idée suite à toutes les motivations mentionnées. Une méthodologie complète a été adopté pour cet objectif en suivant les différentes étapes de mise œuvre : conception des modèles, export des fichiers et importation d'environnement sur le moteur de jeux Unity 3D. L'étude assure un lay-out plus efficace en termes d'action, optimisation de mouvement et disponibilité des composants dont l'utilisateur aura besoin au long de sa formation. Nous avons choisi l'Assemblage comme étape très essentielle dans le processus de maintenance dans l'unité de pompage ciblé par ce projet. Pour cela, un scénario de scène a été présenté pour bien décrire quelques parties de cette intervention en suivant la procédure d'opération présente sur le même environnement. Ce papier est une transition avant de faire l'export et exploiter l'Environnement en choisissant les appareils proposés dans le même chapitre.

Cette étude constitue une nouvelle découverte et propose des nouvelles approches dans le domaine de maintenance en exploitant les technologies de réalité virtuelle et augmentée. Cela prouve de plus une ouverture vers l'industrie 4.0 et les nouvelles technologies. Les objectifs étant de poser un cadre d'application théorique en utilisant les deux technologies pour le même domaine (maintenance) a été atteint. Pour nous, c'est un pas vers la combinaison des deux technologies dans le futur pour le même but : l'amélioration de la maintenance.

RECOMMANDATIONS POUR LES TRAVAUX FUTURS

Cette partie représente les horizons qui peuvent être explorés à partir des résultats de la recherche réalisés ainsi que les suggestions pour approfondir le sujet dans l'avenir :

- L'intégration de la RA avec l'Internet des objets IoT : Pour la première application, cela pourra donner aux utilisateurs accès aux données et aux informations de l'équipement en temps réel que cela soit pour le domaine manufacturier ou le domaine minier, en facilitant l'identification des problèmes, la surveillance à distance et l'obtention des recommandations de réparation basé sur l'état du composant.

- Compléter le processus de construction d'application et valider l'étape d'export du moteur de jeux pour les deux application RA/RV : Finaliser les environnements et les interfaces des deux applications et choisir par la suite les appareils proposés.

- Coupler les deux technologie RA et RV dans une même application pour plus d'interaction et animation : assurer l'intégration des détecteurs de position des différents composants de l'environnement virtuel en assurant un bon rendement de production ainsi une amélioration du volet de sécurité.

- L'adaptation de la RA comme application dans le secteur minier: développer un concept d'inspection et maintenance exposant des données en temps réel à condition de surmonter les obstacles qui pourront empêcher le bon fonctionnement (surtout pour le Tracking) vis-à-vis des conditions du milieu de travail (poussière, bruit …).

- Transposer les méthodologies sur d'autre nature d'opérations non seulement l'Assemblage pour l'environnement virtuel : Élargir la nature des opérations en partant des opérations d'inspections vers le remplacement des pièces de défectueuses.

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