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# Augmented reality assisted calibration of digital twins of mobile robots

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**Abstract:** In this age of globalisation and digitalisation, industry is evolving from a physical space information flow towards a two-way communication between virtual and physical space. The challenge that this research aims to resolve is: 'how can a virtual system adjust itself to the constantly changing conditions of the physical space of information that influences the operational dynamics of maintenance in industry?'. This article presents an augmented reality (AR) assisted digital twin (DT) solution that can be used to calibrate mobile robots in maintenance environments. This DT solution was achieved by providing the user the ability to predict the battery charge of the mobile robot by using historic data as the input and providing the user a visual representation of the mobile robot's movements using an AR device as a medium to display this digital data. Overall, the trial demonstration was a success in implementing a DT to calibrate a mobile robot with AR assistance. Therefore, this DT solution can be implemented into niche areas of industrial environments. With the capability of predicting the battery charge enabling the user to know when the mobile robot will be empty, the user can maximise its use before recalling it for the charge. This would improve the accuracy of scheduling when mobile robots can be deployed and maximise the utilization of the robot and reduce the running cost of mobile robots in the long term.

*Keywords:* Digital Twin, DT, Augmented Reality, AR, Mobile Robot, Prediction.

## 1. INTRODUCTION

Industry is evolving from a physical space information flow towards a two-way communication between virtual and physical space (Tao et al. 2018; Zhuang et al. 2018; Tao and Zhang 2017). While virtual and augmented reality (AR) technologies are becoming practical tools in support of a DT vision where immersive and collaborative artificial-reality also supports design of human-robot workspaces and automated manufacturing systems (Malik et al. 2020; Masood and Egger 2020; Kuts et al. 2019; Liu et al. 2019) and future-proofing of through-life engineering services (Masood et al. 2018), recent literature also reports on AR challenges and success factors in its industrial adoption (Egger and Masood 2020; Masood and Egger 2019).

A DT is defined as a system that represents "an accurate digital representation of the physical object's data values, states, and properties (e.g. shape, position, and/or throughput) which can be obtained through sensors attached to physical objects" (Kritzler et al. 2017). The physical space information flow consists of information manually collected from the source of the activity (e.g. shop floor activities) and the reliability of this information is dependent on how the information is collected. As integration and reliance on technology continues to grow within industries, the demand to merge the virtual and physical space has increased. Harmony between the virtual and physical space can be obtained by removing the miscommunication of information from any process that requires human input. Removing the human factor and automating the transfer of information from a virtual space (e.g. analysis techniques performed digitally) to the physical space (e.g. machines or objects adjust to account for changes needed) will play a vital role in the years to come. Achieving this stage of the cycle of information flow is paramount for improvements in operational efficiency and effectively utilising all resources available within a shorter period. To achieve total transparency between the virtual and physical world, a DT can be used to bridge the gap between physical and digital information flow. The information sent from the physical object is used to accurately update its digital model in real-time in order to monitor physical characteristic changes and provide an opportunity to predict behaviour changes in advance and identify emerging anomalies, so that optimised solutions can be implemented to ensure the reliability and efficiency remain high or improved (Ponomarev et al. 2017). Furthermore, communications between multiple physical objects and systems could be modelled as a DT (Kritzler et al. 2017). Kritzler et al. and Ponomarev et al. (2017) state that the DTs embody the entire life cycle of any product or system, from Enterprise Resource Planning (ERP) to live operational data. However, DTs are most suited for automated systems as they try to minimise human input to reduce human error. Therefore, a "DT can be seen as a digital construct of a physical system" (Kritzler et al. 2017).

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The aim of this research is to demonstrate the capabilities of a DT using a desktop application and AR (as a visual assistance) to calibrate the DT of a mobile robot. The motivation for this study is to integrate AR with (DT) that can be used to calibrate mobile robots in maintenance environments. The wider motivation is to illustrate the potential of integrating AR and DT in mobile (e.g. planes, ships) and adaptive systems (e.g. degradation) to enhance the performance and productivity of assets. The objectives of this research are:

- To explore opportunities where AR and DTs can be used in a maintenance environment,
- To develop a DT application that can predict the battery status of a mobile Robot,
- To use AR to illustrate the movements of a mobile robot,
- To demonstrate accuracy of a calibrated robot, and
- To test the accuracy and precision of the tools.

The rest of the article is structured as follows. Section 2 provides analysis of literature on the topic. Research methodology is presented in Section 3. Section 4 proposes a DT architecture while results are discussed in Section 5 before concluding in Section 6.

## 2. LITERATURE REVIEW

This section presents a literature review on “digital twin” and “visualisation”.Meta-analysis method was used for conducting a literature review. An analysis of multiple studies related to criteria set by keywords was done. ‘Digital Twin’ and ‘visualisation’ were initially used to obtain the first set of papers required for the literature review; this resulted in a collection of 1,858 (Scopus) and 121 (Google Scholar) which ranged from 2005 to 2018. These papers were then filtered by analysing the title and abstract relating to maintenance, the utilisation of DTs or the use of AR with DTs; which provided the final pool of 43 academic papers; from Scopus and Google Scholar. The literature analysis highlights the following subjects: hardware display devices, current applications, hardware data collection devices, digital information obtained, future development, challenges and benefits of a DT. In addition, papers based on ‘DTs’ were also considered as part of the study to understand where DTs have been used and which capabilities have already been demonstrated. With these criteria, the analysis of the papers obtained was conducted by adopting the PICOC (Population, Intervention, Comparison, Outcome, and Context) methodology which consists of:

- Population – the sample of papers are from papers related to immersive and visual display.
- Intervention – the utilisation of a DT.
- Comparison – comparing between different applications.
- Outcome – using Key Performance Improvements (KPI’s) to measure the performance of the DT.
- Context – the application will be orientated around the manufacturing environment as this is a vital demographic for many industries.

Research gaps were identified based on analysis of 43 academic articles (Table 1). One area identified across 14 out of the 43 papers evaluated, includes improvements to the Internet of Things (IoT) network connection and big data analytics. Another area highlighted across 12 of the 43 papers were about the implementation of intelligent DTs, which implies autonomous twins, which do not require human input and relies on AI.

The other area identified was the application of DTs for more complex products, which refers to utilising DTs for multiple objects rather than a single object. For example, a DT could be used to monitor a fleet of aircrafts. Data from each aircraft can be used to identify faults early and determine, which aircrafts may experience the same fault. Thus, reducing time and risk of manually searching all aircrafts. Furthermore, using a twin to monitor large processes such as the supply chain and monitoring assets within the supply chain can be beneficial to improving all areas of the company. However, the research that is missing includes prediction analytics related to a moving object. Nine out of 43 papers refer to predictive analytics as an area of future development, but none specify the use of moving object; especially a mobile robot. Furthermore, the other area that is missing is an investigation into AR interacting with a dynamic asset as part of a DT.

Therefore, based on the identified research gaps, the aim of the research presented in this article is to demonstrate the capabilities of a DT using a desktop application and AR (as a visual assistance) to calibrate the DT.

**Table 1. Research gaps in DT domain [based on 43 articles]**

| Research gaps in DT domain | No. of articles |
|---|---|
| Improvement of IoT network connection and big data analytics | 14 |
| Continuous interaction between real and virtual environments | 12 |
| Application for more complex products | 12 |
| Expansion of database repository | 11 |
| Real-time monitoring of a changing asset | 10 |
| Intelligent systems (i.e. autonomous) | 10 |
| Predictive analytics | 9 |

| | |
|---|---|
| Iterative optimisation | 7 |
| Visualising different aspects for specific users | 6 |
| Can be used for creating new products | 5 |
| Scalability | 5 |
| Self-learning | 4 |
| Multi-dimensional modelling | 4 |
| Higher fidelity | 3 |
| Revise methods of collecting data | 2 |
| Use AR for digital twin | 2 |
| Linking meta data to inspection data | 1 |

## 3. RESEARCH METHODOLOGY

The methodology adopted for creating the DT solution is agile software development (Figure 1). This involves monitoring the change of environmental variables such as “requirements, time, resources, knowledge, technology, etc”. The architecture of agile software development using the sprint method was used.

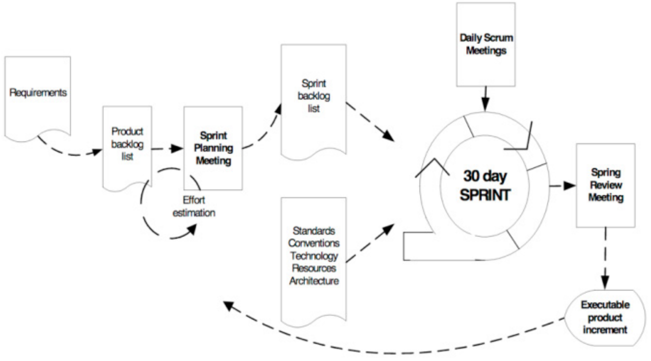


*Fig. 1. The Sprint - Agile Software Development Methodology (Abrahmsson et al 2002)*

For this research, the development of the solution was split into three sprints. The first sprint involves defining the requirements for calibrating a mobile robot. The software requirements involved setting up a software, which is compatible with providing commands to the mobile robot; as the robot used was Arduino board naturally Arduino was the first environment which was setup. Part of this setup involved planning what functions were needed from Arduino to communicate with the mobile robot and print information for post-processing.

In addition, the variable that will be used to demonstrate the DT capability was defined (i.e. predicting the battery charge). This instigated a product backlog list which consisted of obtaining libraries needed to obtain the functions required for moving and obtaining data from the robot. Once completed, the next stage was identifying the prediction software needed to obtain a prediction of the battery charge and identifying the architecture of the DT using existing literature as inspiration. These issues were discussed within the planning meeting stage. Once the backlog list was clear and the architecture was designed, the requirements and architecture for the prediction software could then investigated. This illustrates a repeat of the first 5 stages of the cycle. After each investigation, weekly meeting took place to monitor the progress of development. This cycle repeated for the testing and validation stages of the project development.

## 4. DT ARCHITECTURE

A DT architecture (Figure 2) was designed from following requirements of the DT solution. The main purpose of the end-product was to provide a demonstration of an application that can predict the battery charge of the mobile robot in real-time and be able to compare the movements of the robot (using AR) with the physical track. This involved:

- To transmit commands to the mobile robot from a digital device and receive data from onboard sensors.
- Ability to perform prediction calculations and obtain an equation which can be implemented into the commands transmitted to the mobile robot.
- Ability to display predicted battery charge.
- Ability to display mobile robot’s position in real-time.

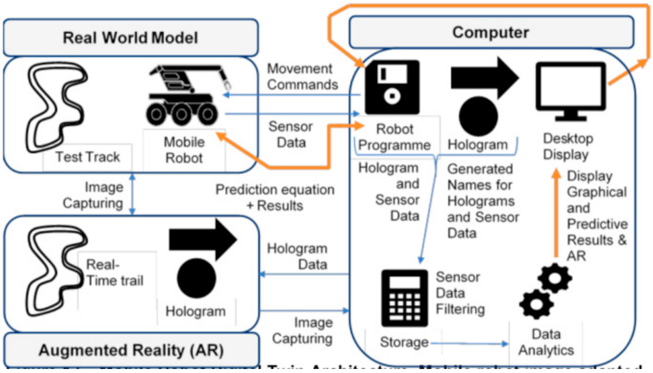


*Fig. 2. Mobile Robot DT Architecture*

This use case replicates the real industrial application of the system in terms of moving objects, which deteriorate over time (E.g. planes, ships, and trains). The integration of AR and DT enables better use of data in real time and enhances decision making capabilities. To fulfil the requirements listed above, the following steps were taken to build the final architecture displayed in Figure 2.

1. The first stage involved setting up a track that the robot will follow in the real- world and will be used as the case-study. This enabled the creation of the first module.

2. This has two parts:

   a. The robot needs to communicate with a device which can run *Arduino* (as this is the only software compatible with the *Arduino mobile robot*). As Arduino is a desktop-based software, a desktop/laptop was used as the second module. This established the two communication between the 'mobile robot' and the 'robot programme' within the computer module.

   b. A hologram that uses a real-world image to initiate the augmented trail is created using a 3D object-oriented programme (e.g. *Unity* and *Vuforia*) which is deployed from the desktop to an AR device (e.g. tablet).

3. As Arduino does not store data long term, the data must be transferred to another local storage facility within the desktop device.

4. This data is then processed using a data science software (e.g. *Rapid Miner*) which can perform data analytics to obtain and display the predictive results. This creates the link from the storage to the data analytics which intern displays the results in the form a graph or table illustrated as the desktop icon.

5. The prediction equation is then obtained and inputted into the robot commands which is sent to the robot and returns the predicted results (indicated as the orange path in Fig 3).

6. As the robot moves around the track, the AR device tracks the position of the mobile robot in the form of a hologram (a digital model overlaid in the real-world). This device is then able to take an image shot and can send the data back to the computer module. Thus, completing the cycle of the DT.

## 5. RESULTS AND DISCUSSION

The results and discussion on application of the DT architecture is presented in this section.

### 5.1 Results and analysis

Figure 3 shows a mobile robot that was built for the purpose of this research.

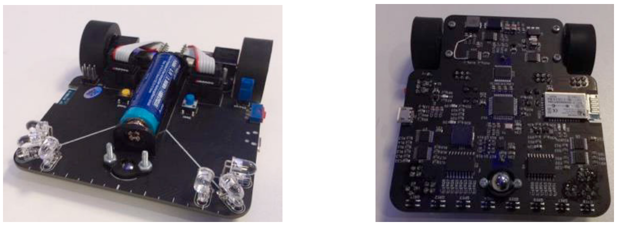


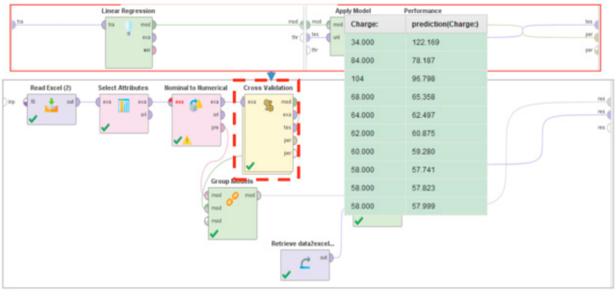
*Fig. 3. (a) Front side of mobile robot, (b) Back side of the developed mobile robot*

First, the data recorded was imported from *Arduino* to *Microsoft Excel*, the charge was then calculated in the form of a percentage by using equation, Eq. (1):

$$Charge = ((Current\ Voltage - 3.7V) / (4.2V - 3.7V)) * 100 \text{ ------------------ } Eq.\ (1)$$

*(3.7V = 0% battery charge and 4.2V = 100% battery charge).*

Then two methods were considered for predicting the battery charge. The first involves plotting the results of the current charge of the battery. Then using the forecast function in *Microsoft Excel* to obtain the equation of the line ($y = (-0.279*x) + 58.422$). As time is x variable in this linear equation, the next time number could be inputted, and a prediction was calculated based on an offline prediction model (Figure 4). As *Microsoft Excel* is not always accurate, *Rapid Miner* (an analytic data science software that specializes in calculating predictions) was also used to perform a more in-depth analysis and prediction of the results recorded.



| Charge: | prediction(Charge:) |
|---|---|
| 34.000 | 122.169 |
| 84.000 | 78.187 |
| 104 | 96.798 |
| 68.000 | 65.358 |
| 64.000 | 62.497 |
| 62.000 | 60.875 |
| 60.000 | 59.280 |
| 58.000 | 57.741 |
| 58.000 | 57.823 |
| 58.000 | 57.999 |

*Fig.4. Rapid Miner Offline Prediction Model*

This research provides insights into existing state of the art and experience of designing and implementing DTs into industrial operations. The requirements for calibrating a mobile robot and features that demonstrate a DT capability were mapped and used to form the basis of the conceptual design. The DT solution was developed by creating a line following programme, which provided the initial data to create a prediction equation for predicting the battery charge (Figure 5). An AR interface was then created to display the movements of the mobile robot in real-time by displaying a digital trail after the mobile robot's current position.

Figure 6 illustrates the various positions of the mobile robot (y-axis) over time (x-axis). The centre of the track (indicated in green) illustrates the neutral position of the robot whiles the other colours represent the offset position of the mobile robot. In Figure 6, majority of the results are clustered around the neutral position (0 deviation), which demonstrates the accuracy of the calibration at 60%.

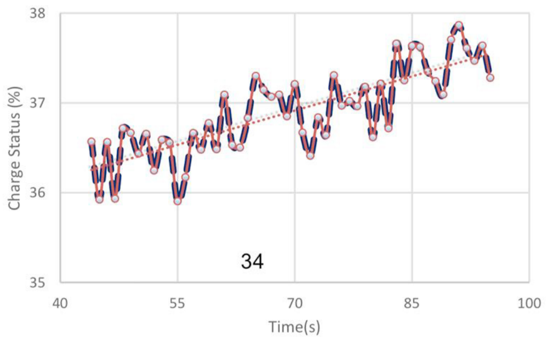


*Fig.5. Prediction of battery charge*

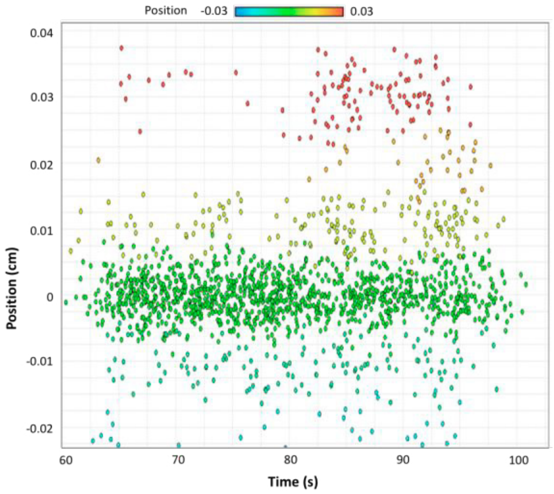


*Fig.6. Position of mobile robot with the factor for the rotational velocity at 0.15m/s*

The final DT solution illustrates the capability of predicting the battery charge status in real-time and AR assistance, which consists of an augmented image of the robot's movements overlaid onto a real-world track using a device that supports AR software (e.g. a tablet). The first validation consisted of determining the accuracy of the predicted battery charge. As a result, the accuracy of the prediction model when the speed factor was set at 0.15m/s was 88% accurate within a tolerance of +/-0.05% tolerance and an error of 2%. The second validation consisted of the position accuracy of the mobile robot as it followed the fixed track. With the speed factor at 0.15m/s, the position accuracy was 89% with a deviation tolerance of +/- 0.02mm. The final validation consisted of a visual comparison between the real-world track and the movements of the mobile robot; represented by an augmented trail behind the mobile robot. As a result, the DT calibration worked; as the mobile robot stayed on the track for majority of the time.

### *5.2 Benefits and Drawbacks of the Application*

The benefits of the application include the ability to predict the battery charge in real-time accurately and AR can be used to track the movements of the mobile robot. The drawbacks of this system are that there is significant amount of offline processing required before the robot can transmit the predicted charge values. Furthermore, the DT relies on Arduino for data collection, Rapid Miner for predicting the data required and Microsoft Excel for obtaining the prediction formula which needs to be manually input into Arduino. In addition, Vuforia and Unity are required for tracking the mobile robot in real-time; which is not accurate as the targeting system losses its target around corners and at certain distances. Overall, having separate systems makes it difficult to operate this DT. Due to software limitations, it is currently not possible to form connections to transmit, receive and display data between Arduino and Unity. However, there has been some development, but more transparency between software is required if a fully functional automated DT is to be created.

### *5.4 Challenges addressed*

The academic challenges addressed from this DT includes creating a real-time AR monitoring system, which illustrates the movement of a dynamic object to a certain degree, the creation of a DT, which can predict a variable of a dynamic object. The industrial challenge addressed is the creation a DT for calibrating a mobile robot, which has prediction capabilities and is a good starting point for building more sophisticated DTs with multiple capabilities such as optimisation and utilising various data to predict physical change of the asset rather than a chemical one (i.e. battery charge depreciation over time). Overall, this work demonstrates that it is possible to create a DT which can predict a variable which has not been done for a mobile robot. Furthermore, this work has also demonstrated the limitations of using AR to track a dynamic object; as specified above.

## 6. CONCLUSIONS

A DT has been created with prediction capabilities which can determine when failure will occur (i.e. predicting when the battery charge reaches zero). In addition, AR has been used to track and overlay 3D images to illustrate the calibration of the mobile robot. The solution has accuracy of 88% when predicting the charge and a position accuracy of 89% with a deviation of +/-0.02mm. However, the precision is 49.94% +/- 0.12%. Furthermore, AR has been used to illustrate the movements of the dynamic mobile robot, but has also demonstrated that it was not precise enough for determining the accuracy of the calibrated robot.

Even though there has been some development of DTs for industry, future research may focus on refining the solution discussed in this article and future DT applications. A few suggestions follow:

- Standardising the solution by using a single platform for building a DT.
- Applying machine learning, algorithms and artificial intelligence to process prediction data and other types of data such as process optimisation and to reduce the number of software packages used.

- Introducing optimised velocity factors, speeds or voltage settings for the motor.
- Using other sources of information e.g. stress, strain results, temperature, varying environment settings and create a system twin.

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