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Prediction and estimation model of energy demand of the AMR with cobot for the designed path in automated logistics systems

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Abstract

The ecosystem of the Industry 4.0 involves many new technologies, such as autonomous mobile robots (AMR) and cobots (collaborative robots), these are characterized with higher flexibility and cost effectiveness which makes them more suitable for automated internal logistics systems. The evaluation of energy consumption of AMRs for a designed path in a real case scenario using analytical tools are challenging. This paper proposes a method of evaluation of the sustainability of new technologies of Industry 4.0 in internal logistics.
The proposed framework demonstrates data management technique of the industrial robots. Since, the AMR with manipulator perform different tasks as a single system in logistics there is big demand to develop model of cyber physical system. During task execution measured robots' physical parameters used as input data to perform analytics. Moreover, acquired data from different condition use cases have been used to monitor the battery behaviour of the AMR and preliminary results of the linear regression model is presented.

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Keywords: Cobot and AMR; Battery prediction; Linear regression model; Industry 4.0

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1. Introduction

The Emerging technologies of Industry 4.0 (I4.0) are providing opportunities to improve logistics systems. By adopting new tools of I4.0 such as IoT, AMR and advanced information technologies, industrial enterprises can optimize the management and structure of the current logistic systems and build more convenient and efficient automated logistics infrastructures. Moreover, the management of such logistics systems can significantly improve the economic situation of industrial companies. However, automated logistics systems integrated with new technologies within AMR and other types of robotics in the era of Industry 4.0 are still open for research. At the moment, robots in logistic systems serve to manage the flow of materials mainly in packaging, palletizing or to connect two different workstations and widely used robots in logistics are so called AGV or AMR. The AMR that has been used and studied in this paper differs from traditional AGVs and other logistic robots. The main features of AMRs compared to AGVs is their ability to sense the environment and respond to it in real time if necessary, also in-route planning and decision-making can be done dynamically and all these behaviors and functions are integrated into one system. The system is smart enough to calculate the optimum trajectory to reach the target by avoiding obstacles and the AMR navigates itself through self-constructed maps. That's why it is easy and cost-efficient to implement in automated internal logistics systems. Besides the above-mentioned features, AMRs can be controlled by users using tablets or mobile devices, this added functionality arises from the fact that these robots are much easier to program than traditional robotics and require little programming knowledge. The system gives opportunity to users to control the logistics of the robot anytime and from anywhere. For example, they can access its dashboard remotely to control or monitor in real-time the robot's parameters and status indicators while

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viewing the exact position of the robot on the map. Moreover, AMR uses proximity sensors, laser scanners and integrated cameras to acquire data from the environment and they are powered by batteries. Analyses of battery capacity of AMRs are another important factor. Battery level prediction for designed paths could serve as additional information that can be used to improve the performance and sustainability of multi-robot systems in logistic systems or in warehouses.

Cobots are designed to interact with a human directly and physically that's why they can work in collaboration safely in a shared workspace.

Since manufacturing processes are complex and involves thousands of interconnected industrial components. Unexpected interruptions of cobots and/or mobile robots in manufacturing processes such as mechanical failures, unplanned maintenance, hardware or software problems, and vehicle breakdown during transportation, traffic delay or wrong delivery may lead to losses money of the company.

The Objective of this paper is to present preliminary results of the proposed framework that evaluates energy demand of the AMR when it works alone and with cobot mounted on it. These analyses are useful to create automated internal logistics management systems with battery powered system that composed multi mobile and/or collaborative robots.

The paper is divided into following parts: (i) developed an experimental setup for internal logistic scenario to evaluate energy consumption for a designed path, (ii) data driven approach to analyze energy consumption of AMR alone and with manipulator in different conditions for a designed path is performed, (iii) results of predictive model to evaluate energy demand of robots are presented.

2. Related works

Current emerging tools and technologies are providing more opportunities to improve the performances of AMR/AGVs in logistics system and researchers are proposing several solutions for the prediction of battery consumption of AMRs when robot manipulators are mounted together in automated logistics. In order to satisfy demand of the automated logistics systems seven activities must be respected [1,8]: availability of the product/service, in the right quantity, in the right condition, at the right place, at the right time, for the right customer, at the right cost. In order to manage these requirements in a paper [9] proposed an algorithm that extends Dynamic Window Approach (DWA) for energy efficient path planning navigation using cost function based on energy consumption of mobile robots. Estimated energy consumption during planning is predicted using a linear regression model. The results of the model decrease the energy consumption of the mobile robot for 9.97% compared to the DWA model. In [4,5,6,7] proposal of energy model for lifts and automated guided vehicles used in automated warehouse solutions are presented.

Energy consumption prediction model of battery powered cars based on real-world data is proposed by authors [11] they used multiple linear regression based on dynamic equations of the vehicle to construct their models. The models used as input the parameters of distance, travel time, temperature, acceleration data and other kinematic parameters to predict the energy consumption.

To evaluate robots' battery level in multi-robot scenarios for internal transportation systems the authors [10] predict the battery capacity of individual robots during run-time of the system.

Authors of [2] made analyses on collaborative task execution between AMR and manipulator robot and they demonstrated a fruitful collaborative interaction among three main actors of the factory of tomorrow: the human operator, the mobile robot and the manipulator

Acquisition of required data from collaborative and mobile robots within the measuring performance are studied in [3]. Authors demonstrate the operation of data acquisition system for collaborative and mobile robots and the real–time monitoring dashboard. The outcome of the study is the gathering of data at field level, the evaluation of robot performances at machine level in order to execute the real time production control at factory level.

In comparison to the above reviewed literatures our model uses physical and environmental data including positional and battery data of the AMR when robot manipulator is mounted and performing tasks together and separately in planned path of logistics systems. The conducted experiment is a real life scenario of a logistics system and collected real time data is driven to the model to perform analytics and further to do predictive analyses of energy consumption of AMR when manipulator is mounted on it.

3. Process flow of the experiment

The workflow depicted in figure 1 was performed to generate automated internal logistics system using collaborative robot mounted on the AMR and evaluation of energy consumption of AMR in different conditions while performing transportation tasks.

As per figure 1, starting point of workflow is the connectivity architecture, which outlines the structure of the data set, connectivity configurations and the specifics of data exchange. In this step, the hardware data of the AMR has been derived from a full bundle of available hardware health data readings according to predefined objectives (evaluation of energy consumption), data acquisition methods and techniques, as well as data flows are defined.

Subsequent step of the workflow describes structure and details of the design of the experiment. In this step physical characteristics, such as loading parameters, trajectory and sequence of tasks for the AMR are defined.

Experimental use case outlines the conduction of the experiment using the parameters and details predefined by previous steps of the general workflow, which is followed by an aggregation process of generated hardware data in the storage.

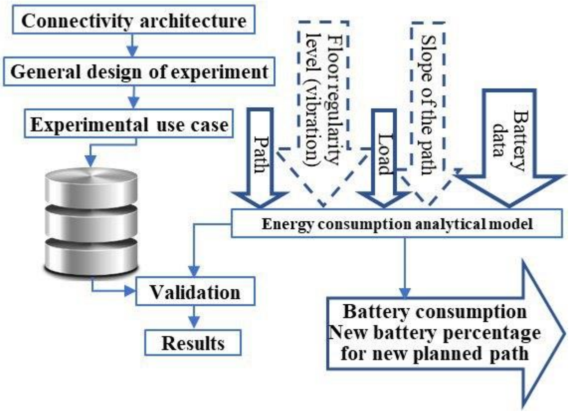


Fig 1. General approach of the energy consumption evaluation of AMR for internal logistics.

4. Description of components and networking architecture of the experiment

This section describes communication protocols and data exchange architecture used for the experiment. In order to acquire data from the generated system, the components and tools shown in figure 2 have been used. According to the figure 2, components have been divided into Factory/LAB and Cloud levels.

At the Factory/LAB level, the autonomous mobile robot (MIR100) has been used as the edge device to transport heavy loads, Wi-Fi access point (AP) has been engaged for supporting wireless communication, and the central PC with Node-Red instance installed. Moreover, at the Cloud level, cloud based MQTT broker service and database server with Node-Red have been utilized for Factory/LAB level generated data retrieval and storage.

4.1. Description of data exchange between connected devices

In order to systematize the description of the structure and elements of the experiment, the TCP / IP protocol stack was chosen, which reflects the communication model of the experiment.

According to Figure 3, based on the TCP/IP protocol stack at each level the communication model represents the devices, protocols, and technologies that were used to implement the experiment.

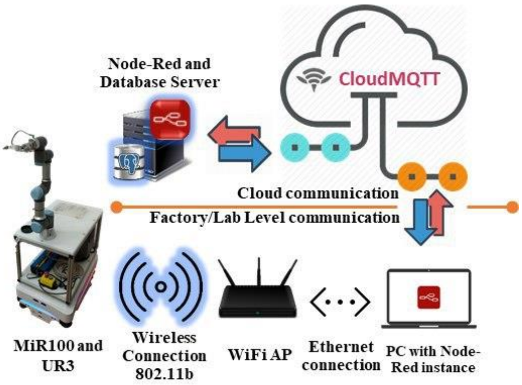
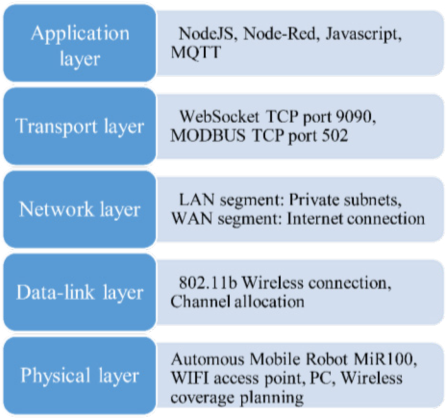


Fig 2. Networking of components.



Application layer	NodeJS, Node-Red, Javascript, MQTT
Transport layer	WebSocket TCP port 9090, MODBUS TCP port 502
Network layer	LAN segment: Private subnets, WAN segment: Internet connection
Data-link layer	802.11b Wireless connection, Channel allocation
Physical layer	Automous Mobile Robot MiR100, WIFI access point, PC, Wireless coverage planning

Fig. 3. Communication model based on TCP/IP protocol stack.

PHYSICAL LAYER. From the point of view of this layer, the MiR100 autonomous mobile robot, Wi-Fi AP, PC and Network coverage plan were involved. An autonomous mobile robot performed a pre-planned set of tasks (instructions) for the transportation of goods with various masses and the trajectory of movement. The access point was the link between the computer and the mobile robot, providing communication for the exchange of data. A computer was used to collect data on the state of the hardware of the mobile robot under various operating conditions. In order to ensure continuity of communication between AMR and the computer, a network coverage plan was developed to determine the optimal location of the access point in the experimental area.

DATA-LINK LAYER. The wireless network was built on the basis of an access point with an omnidirectional antenna with the following parameters:

Wireless network standard: AMR movement paths on the experimental area implied the presence of reinforced concrete obstacles and long distances, which in turn created additional requirements for ensuring the continuity of communication and devices staying within the reach of the wireless signal. Taking into account the above requirements, as well as the specifics of data exchange between AMR and a computer (Raspberry), the 802.11b standard was chosen.

Bandwidth: 11 Mbps. This bandwidth was enough for data exchange between the AMR and the computer, taking into account the fact that data from the AMR was requested at a frequency of 1 Hz. At the same time, the network delay was up to 10 ms.

Channel allocation. The working channel for the wireless network was channel 13 with a central frequency of 2472 MHz. This choice meant preventing interference and blocking of other channels of wireless broadcasting (public wireless network).

NETWORK LAYER. Two networks were configured to provide data transfer from AMR to the MQTT cloud service:

Local Area Network - a network that supports communication between AMR and a computer (raspberry);

The Internet network - a network that ensures the transfer of data received from AMR to the MQTT cloud service.

TRANSPORT LAYER. The data on the status of hardware components and sensors were obtained using the WebSocket protocol via TCP port 9090, whereas the data on the AMR position via MODBUS protocol through TCP port 502.

APPLICATION LAYER. To maintain the data exchange (retrieval, transmission and storage) at this level were used:

Node-red, NodeJS, JavaScript – to build a logical circuit for connecting to AMR, retrieval, filtering and further delivering the data to the storage;

MQTT – to coordinate messaging between devices on a publisher-subscriber pattern.

4.2. Description of general design of the experiment

This section reveals the details of the developed design, according to which the use case experiment has been conducted in section 4.3. The figure 4 depicts visual representation of the design. According to the figure, cobot(UR3) mounted on the AMR(MiR100) travels between waypoints: edge waypoints - Supplier/Client (SC), Workstation

(W1) and Workstation2 (W2); interim waypoints – Waypoint with the several loading states (unloaded and loaded with various load). Location of the PC and Wi-Fi AP is chosen considering the provision of wireless signal coverage for seamless connectivity between PC (with Node-Red instance) and MiR100 AMR (while its traveling from waypoint to waypoint).

Waypoints depicted in figure 4 represents the below functional stations:

Supply/Client (SC) – Implies warehouse function - sending of component and receiving of finished products.

Waypoint – Implies interim location, used for routing of the AMR.

Workstations (W1 and W2) – Implies workstation – processing component and production of product.

For creating and replicating a task sequence for MiR100 AMR, the process flow has been developed and used, as illustrated in the figure 5. In process flow the abbreviations have been used to explain waypoints. The process flow begins by moving the AMR to Supply/Client waypoint. After, the cycle is initiated, where the AMR waits for loading and unloading (Load/Unload); moves to Workstation1 and repeats waiting for loading and unloading; moves to Workstation2 and repeats waiting for loading and unloading; finally goes back to starting point - Supply/Client. The cycle repeats up to n times, and after, AMR changes its trajectory beginning its travel at Supply/Client, this time moves to Workstation2, then it moves to Workstation1, and finally travels back to Supply/Client waypoint. MiR100 AMR has a specific mission designer interface where task sequences are built as blocks. Using tools of the interface we built the sequence based on the process flow mentioned above.

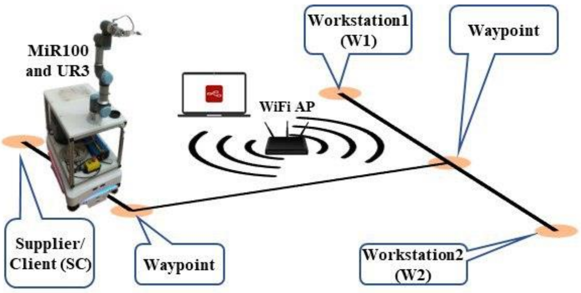


Fig. 4. Visual representation of the experimental design.

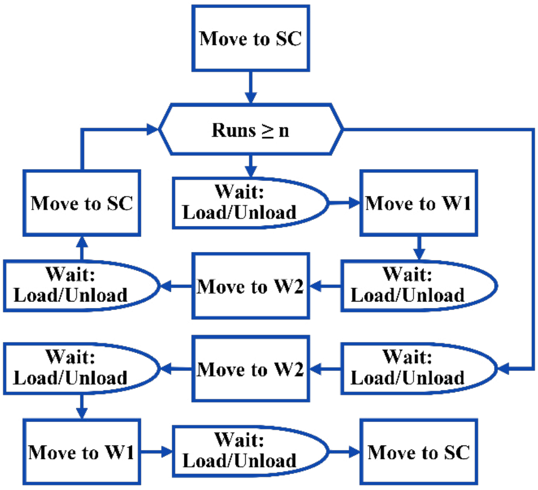


Fig. 5. Process flow of the task sequence for the MiR100 AMR and manipulator.

4.3. Use case experiment design and data acquisition methodology

To evaluate battery behavior of the AMR the experiment has been performed in three conditions: in the first condition AMR moves alone on the designed path and human operator loads/unloads workpieces; in the second phase AMR moves along the designed path with manipulator but it is switched off; in the third phase AMR moves along the designed path with mounted manipulator and every time when AMR arrives to the workstations the manipulator performed loading/unloading tasks.

This section goes deeper in the experiment, therefore elaborating section 4.2 with more practical details.

The use case experiment was conducted in the facility of POLITO. From this sense, initially, facility map building was conducted. AMR was guided and facility map was generated using software, as well as on-board sensors such as proximity, ultrasonic and laser scanner. After map generation, positions of waypoints of AMR was marked in the map, as depicted in figure 6. Figure 6 also illustrates the location of Wi-Fi AP concerning waypoints, with the seamless connectivity idea in mind. Considering specifics of the facility area, interim waypoints were marked for better navigation and routing of AMR (MiR100).

The first phase use case experiment was conducted in the sequence of 5 runs per turn, in different loading states of the AMR alone as depicted in figure 6. The table 1 shows routes

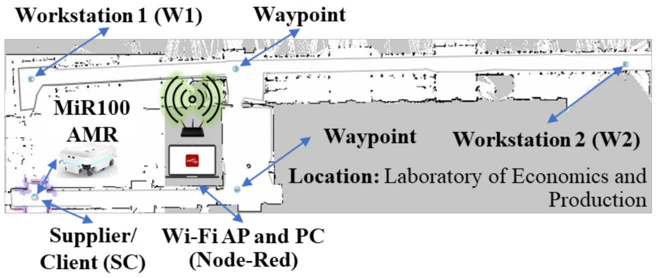


Fig. 6. The first experiment with AMR on the designed map and navigation route with workstations

and corresponding loads. Correlating the data in the table 1 and the process flow in figure 5, the cycle started with no load, following with loads up to 30, 60 and 90 kilograms (maximum load on MiR100 AMR is 100 kg), and then finalizing the turn with last route where Workstations are reversed with no load. During the experiment loading/unloading has been performed by human operator. The loads/unloads have been conducted to observe the battery behaviour during the experiment.

Table 1. Sequence of missions.

Route	Load
SC→W1→W2→SC	Unloaded
SC→W1→W2→SC	~30 kg
SC→W1→W2→SC	~60 kg
SC→W1→W2→SC	~90 kg
SC→W2→W1→SC	Unloaded

Main target readings of MiR100 AMR, during the experiment, were CPU state (load and temperature), battery state, motors and controller, as well as the IMU sensor readings (gyroscope, accelerometer and temperature sensor). The readings were acquired on the PC (with Node-Red instance) and sent to database storage according to architecture, as illustrated in figure 2. The battery discharge of the AMR was the same as indicated on its dashboard.

In the second phase of the experiment the manipulator has been mounted on the AMR, but manipulator has been switched off and performed the same steps as in the first phase. In this phase of the experiment the battery data such as discharge time, capacity of the battery, battery power has been acquired.

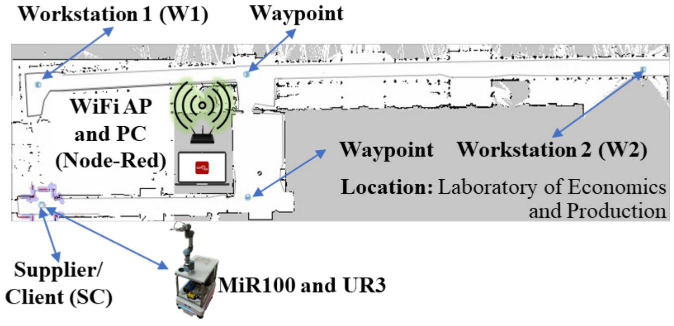


Fig. 7. Second and third experiments with robot manipulator mounted on the AMR designed map and navigation route with workstations.

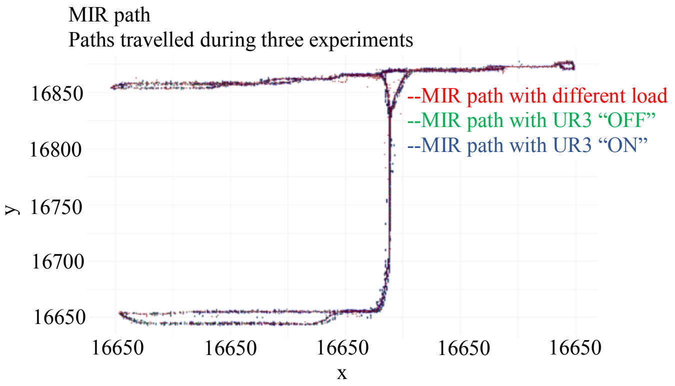


Fig. 8. Traveled paths of AMR during three experiments.

In the third phase, cobot manipulator mounted on the AMR Manipulator has been turned on all the way and manipulator performed loading/unloading tasks in every workstation. The acquired data to the database is battery behavior as in second phase. In Figure 7, cobot manipulator mounted on the AMR to perform second and third experiments have been depicted. acquired data to the database is battery behavior as in second In next section, results of the three experiments have been described and discussed.

5. Results and discussions

To show the results of the battery behavior of the AMR in three experiments the travelled path by the AMR has been observed.

During three experiments the positional data of the AMR have been acquired. Figure 8 shows the travelled paths of the AMR during experiments: red data is first experiment; green is second and blue is third experiment path.

To understand battery behaviour in designed path, remaining battery level during the travel has been acquired for further analytics. Remaining battery level trend of three experiments are depicted in figure 9.

Afterwards, based on the remaining battery level data, linear regression model has been performed. Figure 10 demonstrates linear regression model results of three experiments of battery discharge level. From the graph it is

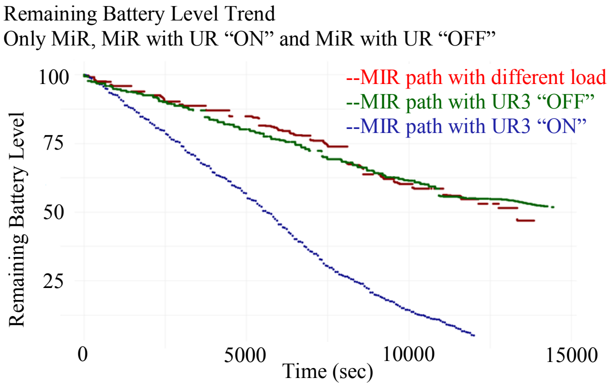


Fig.9. Remaining battery level trend of three experiments: red data is first experiment results: green data is second experiment results: blue data is third experiment results.

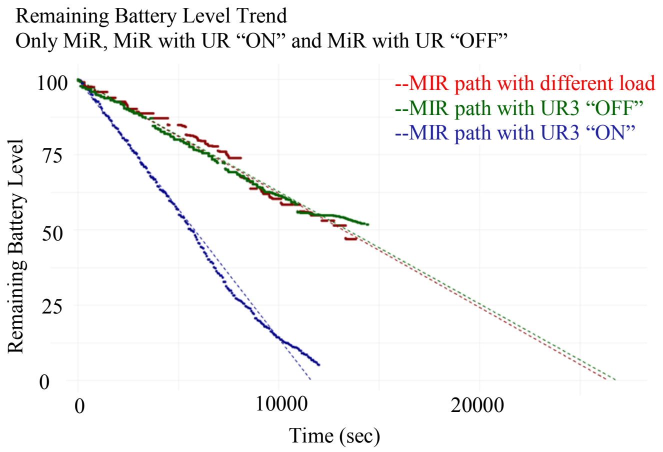


Fig. 10. Linear regression model of three experiments.

clear that when AMR moves with UR3 turned on, the battery discharge time is three times faster than usual cases. The performances of the linear regression model are given in table 2. In this table the time-dependent linear behaviour of the energy consumption is clearly validated by significant general p-values that demonstrate that the time variable is strongly describing the energy consumption and by Adjusted R-squared values greater than 99%.

Table 2. Performances of the linear regression model

Scenario	Std. error	Adjusted R-squared	F-statistic	p-value
MIR	2.195	0.9991	9.148e+06	< 2.2e-16
MIR with UR ON	2.973	0.9973	7.362e+04	< 2.2e-16
MIR with UR OFF	1.839	0.9994	1.876e+07	< 2.2e-16

In Table 3 slopes of linear regressions are shown: negative values indicate the decrease of the battery capacity. From this table is clear that the weight of the manipulator set on the AMR doesn't affect the energy required for the task execution. Contrary, when the manipulator is turned on and has few tasks assigned the energy consumption changes drastically: the slope in this case is almost three times larger in absolute terms respect cases in which only the AMR is working, this value means that energy consumption is almost three times faster so the duration of the battery is almost three times less.

Table 3. Coefficients of the Linear regression model

Scenario	Slope	Std. Error	t value	Pr(>|t|)
MIR	-3.788e-03	3.003e-06	-1262	<2e-16
MIR with UR ON	-8.606e-03	3.023e-05	-284.7	<2e-16
MIR with UR OFF	-3.729e-03	2.141e-06	-1742	<2e-16

6. Conclusions

In this paper the evaluation of battery discharge level of AMR with manipulator for a designed path in a real case scenario using linear regression model is presented. The proposed framework in the paper demonstrates data acquisition technique from robots. To evaluate battery behaviour three experiments have been conducted: The first experiment conducted with AMR alone on the designed path and human operator loads/unloads workpieces; in the second experiment AMR moves along the designed path with manipulator and it has been turned off; in the third experiment AMR moves along the designed path with mounted manipulator and every time when AMR arrives to the workstations the manipulator performed loading/unloading tasks.

During task execution measured robots' physical parameters used as input data to perform analytics. Acquired data from three experiments have been driven to the regression model to evaluate battery behaviour of the AMR and preliminary results of the linear regression model is presented. From the regression is clear the energy behaviour of integrated robots. This result is very interesting considering that the energy model integrated in the AMR is not able to consider the presence of another robot set on it. The ratio between slopes referring to only AMR and AMR with robotic arm working can be a corrective factor for the estimation of the energy model of the AMR.

As a result, when AMR moves with mounted manipulator and works together battery discharge is three times faster than usual behaviour that gives errors about battery discharge time on the dashboard of the MiR that means dashboard of the AMR doesn't consider UR3 power consumption. Further, manipulator mounted on the AMR for a designed path needs improvements on its dashboard about battery behaviour.

References

[1] Shapiro, R.D. and Heskett, J.L. Logistics Strategy: cases and concepts. West Group; 1985

[2] Aliev K., Antonelli D. Analysis of Cooperative Industrial Task Execution by Mobile and Manipulator Robots. In: Trojanowska J., Ciszak O., Machado J., Pavlenko I. (eds) Advances in Manufacturing II. MANUFACTURING 2019. Lecture Notes in Mechanical Engineering. Springer, Cham; 2019;

[3] Aliev K., Antonelli D., Awouda A., Chiabert P. Key Performance Indicators Integrating Collaborative and Mobile Robots in the Factory Networks. In: Camarinha-Matos L., Afsarmanesh H., Antonelli D. (eds) Collaborative Networks and Digital Transformation. PRO-VE 2019. IFIP Advances in Information and Communication Technology, vol 568. Springer, Cham; 2019;

[4] D'Antonio, G. & Chiabert, P. Analytical models for cycle time and throughput evaluation of multi-shuttle deep-lane AVS/RS. Int J Adv Manuf Technol 2019; p. 1919–1936

[5] Guerrazzi, E.; Mininno, V.; Aloini, D.; Dulmin, R.; Scarpelli, C.; Sabatini, M. Energy Evaluation of Deep-Lane Autonomous Vehicle Storage and Retrieval System. Sustainability 2019; 11, 3817.

[6] D'Antonio, G.; De Maddis, M.; Bedolla, J.S.; Chiabert, P.; Lombardi, F. Analytical models for the evaluation of deep-lane autonomous vehicle storage and retrieval system performance. Int. J. Adv. Manuf. Technol. 2018, 94, 1811–1824.

[7] D'Antonio, G., Bruno, G, Traini, E., Lombardi, F. An analytical model to estimate AVS/RS energy consumption. IFAC-PapersOnLine, 52(13), 2019, pp.24-29.

[8] Jonsson, P. Logistics and supply chain management. New York. 2008.

[9] Henkel, C., Bubeck, A. and Xu, W. Energy efficient dynamic window approach for local path planning in mobile service robotics. IFAC-PapersOnLine, 49(15), 2016, pp.32-37.

[10] Das, P. and Ribas-Xirgo, L., Predicting battery level analysing the behaviour of mobile robot. In XVII Workshop of Physical Agents Book of Proceedings, 2016, pp. 91-98.

[11] De Cauwer, C., Van Mierlo, J. and Coosemans, T. Energy consumption prediction for electric vehicles based on real-world data. Energies, 8(8), 2015, pp.8573-8593.