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ENDORSE Concept:

An Integrated Indoor Mobile Robotic System for Medical Diagnostic Support

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ABSTRACT

Hospitals are considered a field of logistic robotics of high commercial potential and therefore a handful of mobile robots solutions exist. However, they have failed to trigger widespread acceptance by the market. ENDORSE system will pursue 4 innovation pillars: infrastructure-less multi-robot navigation, i.e. minimum installation of sensors and communications buses inside the building for the localization of robots, targets and docking stations; advanced HRI for resolving deadlocks and achieving efficient sharing of space resources in crowded environments; deployment of ENDORSE software as a cloud-based service facilitating its integration with corporate software solutions such as ERP and CRM, complying with GDPR data security requirements; reconfigurable and modular hardware architectures so that diverse modules can be easily swapped. ENDORSE functionality will be demonstrated via the integration of an e-diagnostic support module for vital signs monitoring, facilitating connectivity to cloud-based EHR, and validated in an operational hospital environment for realistic assessment.

Keywords: Intelligent robotics, bioinformatics, e-Health, machine learning, data mining, medical informatics, embedded systems, hardware platforms.

INTRODUCTION

Autonomous mobile robots for the transport of goods and materials are nowadays a well-established solution in large industrial infrastructures and transit warehouses, where they offer significant economic and administrative advantages. In contrast, in spaces such as hospitals, nursing centers, hotels, museums, malls, commercial spaces, offices and retail stores, which herein for economy of space we call commercial spaces, the use of autonomous robots is very limited. The use of existing robotic systems designed for large industrial and warehouse spaces is not applicable to indoor commercial spaces because of the different specifications and different constraints. A fundamental difference is that large industrial and warehouse spaces are characterized by a very structured and predictable environment where robots move in predefined paths and interaction with humans can easily be avoided. Contrary to the industrial warehouses, commercial spaces are less structured, the environment is much more dynamic, and the interaction with humans is frequent. Also, the load specifications are different and the interior architectural specifications are much more constrained.

Automation of the supply chain in commercial spaces could have a high economic impact because a large number of transfers take place per day in these spaces. For example, in a hospital or a health care center, several tenths of person months annually are spent on transfer of goods, linens, biological samples, medical equipment, pharmaceuticals, mail parcels, and of medical waste (more than 850 man-hours per week in a 500 beds hospital) (Ozkil et al., 2009). These transfers are currently carried out manually (by pushing carts for long distances) by nurses or carers. That is a no-added-value job which deprives the patients of valuable nursing services. The same arguments apply to the other commercial spaces listed in the first paragraph. In addition, automation of the supply chain will enable full traceability of the goods and the products from the time of the request till the moment of delivery to the recipient; a well-programmed logistics system will improve the services offered to the end-user (i.e. the hotel customer or the patient and the carer in a hospital) by reducing the response times for each request. Hence, the indoor supply chain is an application that calls for automation and at the same time has high commercialization potential because the involved corporations and organizations hold a huge part of the market, they have specific practical problems, and seek specific solutions for which they are willing to pay.

BACKGROUND

Interior spaces in hospitals and healthcare centers, offer advantages that would facilitate the deployment of mobile robots. They are required by law to meet stringent building codes and therefore, from a robotics perspective, the navigation space exhibits some structure which moderates the technical challenge (e.g. concerning home environments). Moreover, most commercial spaces have reliable and predictable communications infrastructure (e.g. Wi-Fi and cellular connectivity), since it is required for normal business operation (Deyle, 2017). Thus, spaces of hospitals and healthcare centers are rightfully considered the next great field of robotic deployment, after the industrial spaces. Despite these advantages, today, few solutions exist for hospital and healthcare spaces - unlike in the case of industrial spaces -, and these solutions do not trigger widespread acceptance by the market. This is because they require costly and time-consuming localization infrastructure (significant peripheral sensor installation, mapping, etc.); they do not easily integrate to corporate IT solutions; as a result, they do not address data protection and cybersecurity threats satisfactorily; they are not adaptable and reconfigurable and therefore are limited to a single type of service. Existing solutions for small and medium commercial spaces, such as hospitals and healthcare centers, by Aethon ('Aethon - Autonomous Mobile Robots - Industrial, Healthcare and Hotels', 2018), and SwissLog ('Swisslog automation solutions for Logistics & Healthcare | Swisslog', 2018) are costly (>75,000 Euros plus installation costs) and exhibit operational limitations. They lack motion flexibility, and therefore the design and implementation of their route become challenging in small spaces; they are not customizable and modular and therefore perform no tasks other than the transfer of goods; hence they lack the capability to replace their carts with other functional units such as an e-health diagnostic station or a UV-light sanitizer. These systems are difficult to integrate with existing ERPs and business intelligence systems typically installed in healthcare buildings, and therefore the data they collect (from their sensors), and the tasks they execute are not registered in the corporate records and data management system. Cybersecurity threat is another deterrent factor, especially in cases where humans are involved. The solution to the limitations above, and the overall goal of the ENDORSE concept is to design and develop integrated robotic logis systems that enable efficient, cost-effective and safe indoor logistic services for hospital spaces. The specific objectives of ENDORSE, that should be successfully implemented, are described next:

- 1) To develop a cost-effective logistics robotics system for indoor healthcare environments. A key point for the achievement of this goal is the minimization of installation time and the cost of the system.
- 2) To push forward the frontier of Human-Robot Interaction, especially for the cases where the robot should safely navigate in crowded spaces. It is human-robot interaction that should help to resolve deadlocks that involve humans.
- 3) To develop robust localization methods for infrastructureless indoor fleet localization and supervision, which will result in installation time minimization.
- 4) To introduce innovative cloud services that bring together solutions from healthcare, robotics, and logistics and will offer new business models for indoor logistics and high data security standards.
- 5) To develop an integrated e-diagnostic mobile station, which will endow modularity to the ENDORSE system, and will serve as an e-diagnostic mobile station.

The objectives will be achieved by tackling specific scientific and technological challenges through cross-sector collaboration taking advantage of complementary competences on the fields of robotics, machine vision, logistics, IT and product design. The proposed solution will be modular and reconfigurable and thus applicable to different fields and applications of commercial spaces, while at the same time will focus on the needs of the healthcare sector. The developed solution will be piloted in the healthcare center Fundació Ave Maria in Sitges.

CONCEPT DESCRIPTION

The ENDORSE project will realize the objectives above by relying on four main innovation pillars:

1. Infrastructureless multi-robot navigation: Novel internet-based indoors localization technologies will be developed. These will enable multi-robot navigation requiring minimum or no installation of infrastructure on building walls, ceilings and floors (i.e. minimum sensors and communications buses). A typical sensor installation costs over 10,000 euros and requires several days for installation and integration. Hence, this approach will considerably reduce the cost and the time needed for infrastructure installation of indoor logistic systems by fusing state-of-the-art wireless sensors on - the robot with robust Simultaneous localization and Mapping (SLAM) algorithms. The fundamental problem is that there is currently no open-source platform to seamlessly integrate fingerprint measurements from different types of indoor (and robot on-board) localization technologies (e.g., Wi-Fi, BLE, UWB, etc.) (Zeinalipour-Yazti & Laoudias, 2017). We aim to extend the open-source Anyplace architecture with components and specialized localization algorithms, which will enable fine-grain infrastructure-free localization of IoT hardware. We will particularly re-design the algorithmic components necessary for indoor localization, indoor localization accuracy estimation (Konstantinidis, Eracleous, Georgiou, Chrysanthis, & Zeinalipour-Yazti, 2017), API channel optimization techniques (Zeinalipour-Yazti & Laoudias, 2017) and visual analytic cues necessary to provide a rigorous Fingerprint Management Studio for crowdsourced indoor signals. The infrastructureless multi-robot navigation will be implemented by a software architecture that will combine ROS packages implementing the RB1-base navigations and path planning and Java and JavaScript modules for the GUI and the Fleet management system implementation.

2. Human-aware navigation for indoor logistic applications: The robotic revolution is as much about getting the machines to adapt to us as it is about us adapting to the machines. This convergence requires intuitive Human-Robot Interaction (HRI) so that untrained personnel in a healthcare center can interact with the robot to avoid deadlocks, while at the same time the robot can adapt to the crowd and conduct human-aware navigation. Security aspects also play an essential role, so that logistic tasks are addressed to correct persons, including communication systems, message activation and also minimize stress and maximize the comfort of the human who interacts with the robot. These functionalities will be implemented by the perception ROS packages that run on the robot.

3. Reconfigurable and modular hardware architectures: One of the significant innovations and tangible technical outcomes of the project will be the development and testing of the modular interfaces and the e-diagnostic mobile station integrated on the mobile robot and tested in a healthcare environment. That will require research and development in both non-invasive sensors/devices (ECG, blood pressure, oximeter, temperature) and dedicated software applications. To this end, modular hardware interfaces (mechanical, electrical and data interfaces) mounted on the chassis of the robot (commercially available RB1-base by Robotnik as shown in Figure 1), so that different hardware functional modules can be easily swapped. That would be the first time that a medical diagnostic functionality is integrated on a mobile robot. The integrated robot will serve as an e-diagnostic mobile station, which will be able to produce a diagnostic exam report that will be securely forwarded to update and complement the patient's cloud-based Electronic Health Record (EHR). The software of the e-diagnostic mobile station will run on the robot.



Figure 1: RBI-base robot navigating in a healthcare environment (‘Robotnik - Mobile Service Robotics | Robotnik’, 2018).

4. *Cloud-based services:* Cloud Computing contains within it the promise to deliver ubiquitous access to software-based services (SaaS) available 24/7, capable of adapting to varying degrees of user load. Cloud services must guarantee what is known as a Service Level Agreement (SLA). Typically, SLA’s have been customarily specified as some percentage time during which the functionality of the service is available. Guaranteeing the SLA of service is, thus, intrinsically related to the management of the service lifecycle, and the events driving it: initial deployment, reconfigurations, upgrade deployment, fault handling, re-scaling. Automation makes possible to manage the data centers so that they deliver portions of themselves (in the form of virtual machines and networks) cost-effectively. Cloud-based applications will offer to enterprise users a high memory service, data sharing and security. Cloud servers will be able to connect with different individual applications and enterprise legacy systems. The cloud service proposed will contain a repository of algorithms, which will be fed by the data gathered through the cloud. The algorithms in the cloud will allow supporting the management of fleet, including the assignment of tasks to the robots, the queuing functionalities, the generation of dynamic routing and traffic control of the robots, and the supervision the fleet’s task execution. Developing a cloud-oriented software platform will facilitate the development of APIs for integrating ENDORSE software with corporate ERP solutions and health record systems that are often provided as a service in a Cloud environment. Most importantly the ENDORSE applications will comply with the high safety standards for data sharing and data storage which are offered by the Cloud infrastructure. Cloud-based services will run on a cloud server and will be interfaced by the user through a web-based application.

FUNCTIONAL ARCHITECTURE

The concept above is implemented by the system functional architecture depicted in Figure 2. During system operation, five levels of supervision and control naturally emerge, dictated both by time requirement (loop-rates) and the level of abstraction of the signals, which are involved. That leads to hierarchical architecture composed of levels for controlling motors of the wheels, the robot modules, behaviors and tasks, and is described next in a bottom-up sequence. At the lowest level of the hierarchy is the **Signals level**, which involves the process of raw signals, and motor control such as the wheel motors. The second level of the hierarchy is that of the **Motion level**. That represents information regarding the module and its

environment. Each module's controller accepts asynchronous commands to move and turn concerning a standard reference frame. The next level is the Planning level controller. That involves the robot's actions and reactions; it is responsible for online path and motion planning and transforms the current state of the robot to a new state. The next level is the **Task level** where a software platform of the Fleet Management System (Task planner, dynamic robot routing, multi-map manager, elevator controller, etc.) runs. Finally, the highest level of the hierarchy is the GUI level. The GUI level and the Task level can be grouped since these will run on the Cloud, whereas all the rest will run on board.

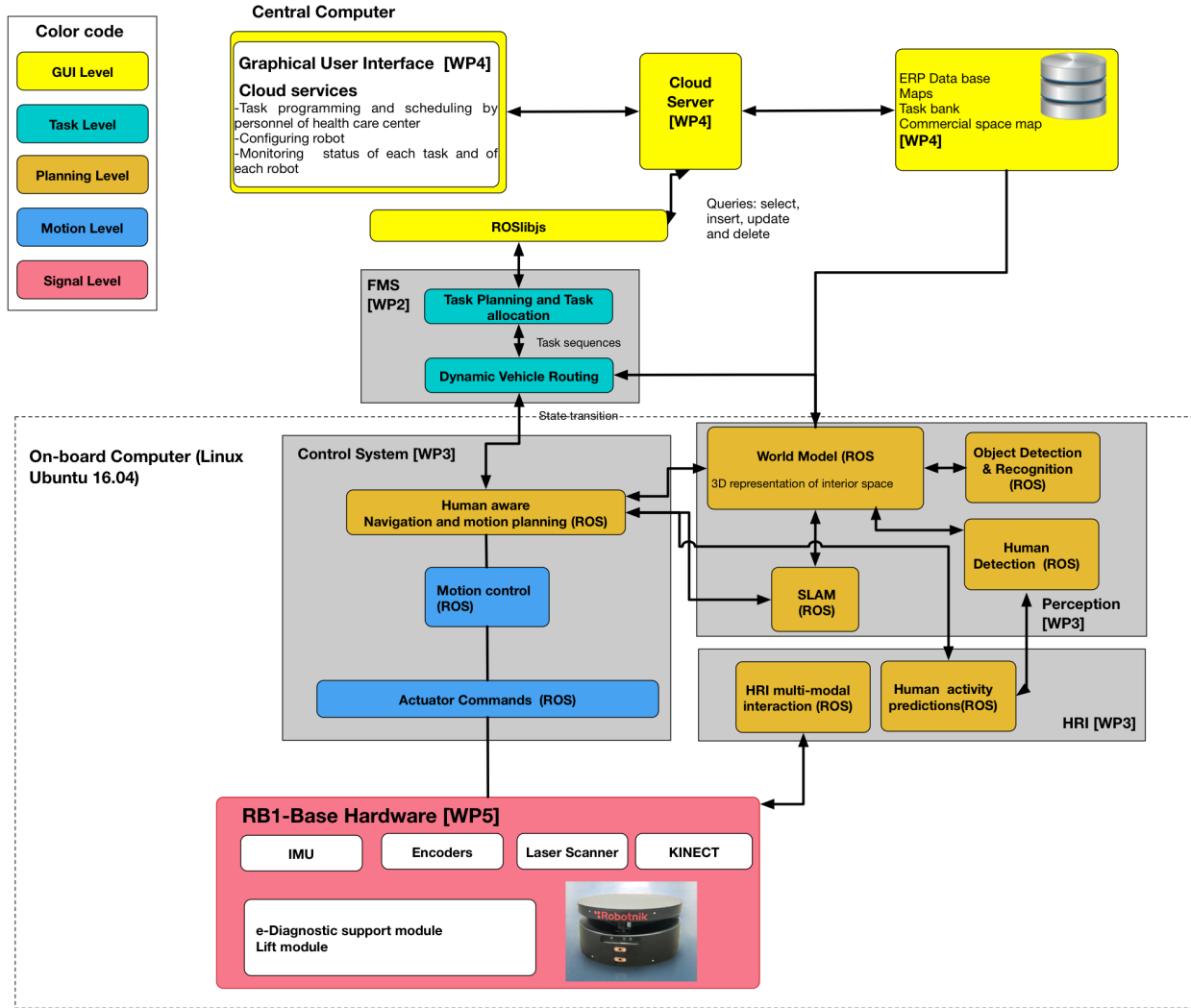


Figure 2: Functional architecture of ENDORSE indoor robotic logistics system.

TECHNOLOGICAL SOLUTIONS

Cloud-based services

In the project, a creation of an API framework will be accomplished, which will integrate logistic robotics into the corporate IT environment, and enable end-to-end automation (automatic traceability of the transferred goods, update of the ERP databases when transactions are carried out, etc.). Moreover, communication and security standards will be investigated in order to securely transfer data from the robot to the patient's cloud-based EHR. To realize this task, ROS-based software integration will be pursued, where all system modules will be represented by ROS packages and ROS nodes. Non-ROS modules (i.e. Java or JavaScript applications) will have APIs that create objects that can be translated by ROS bridge package into ROS standard objects (topics, services, actions, etc.). Due to its integrative nature, this task will be implemented iteratively and will be tightly interleaved with safety human-robot interaction

protocols. An initial integrated software prototype will be developed given the prioritized system requirements and the output of the implementation. Then this initial prototype will be integrated with the Cloud-based services. The evaluation will be done in an iterative manner resulting in intermediate versions. The unique requirements of the healthcare development are already identified, and the development process will use them as a solid basis. Note that all data pertinent to the testing of healthcare APIs and applications will be a dummy; hence no ethical concerns will be raised.

A diagnostic support module and the EHR interfacing will also be included. That will require research and development in both non-invasive sensors/devices (ECG, blood pressure, oximeter, temperature) and dedicated software applications. These sensors could be based on embedded microcontrollers processing units, with 32-bit ARM-Cortex SoC. This chip will also incorporate a full communication layer that makes the device compliant with BLE4.2, BLE5.0, IPv6, ANT/ANT+ and NFC-A tag protocols. In accordance with other magnitudes, the device could be equipped with a 9-Axis Inertial Measurement Unit (IMU) that makes possible monitoring the activity and real-time orientation. When the diagnostic support module is mounted on the robot chassis, the overall robot will serve as an e-diagnostic mobile station, which will be able to produce a diagnostic exam report that will be securely forwarded to update and complement the patient's cloud-based EHR. It has to be noted that all data used in this task are dummy; hence no ethical concerns will be raised.

Internet-based indoors localization technologies

As it was aforementioned, in the ENDORSE project, localization solutions that will enable almost infrastructureless multi-robot navigation will be developed, so there will be the minimum installation of infrastructure (sensors and communications buses) on the building walls, ceilings and floors, reducing the cost and the time needed for infrastructure installation of indoor logistic systems. In parallel, the robustness of SLAM techniques used by ENDORSE will be enhanced, so that the navigation capabilities of the fleet will be fostered. Standard robot localization or location tracking approaches often rely on state estimation algorithms working in a stochastic framework; they usually show weak performance in the presence of data outliers, systematic errors or invalid model assumption. Besides, most of these approaches require initial robot position to be known at least approximately; hence cannot solve the lost robot problem.

We will develop a more robust and effective alternative, which is offered by set membership estimation and data fusion techniques that work in the bounded-error framework. These techniques can operate efficiently with sparse, asynchronous and heterogeneous measurements while being robust to the presence of non-consistent measurements, inaccuracy in environment modelling, and drift and inaccuracy in the robot evolution model. Furthermore, they can naturally track multi-hypotheses about robot pose, hence offer a solution technique for the robot global localization problem (Amri, Becis, Aubry, & Ramdani, 2015) (Colle & Galerne, 2017).

In ENDORSE project, a comparison and a selection of onboard sensors, that are employed for localization, will take place, in order to improve accuracy and stability of global localization (localization techniques fail, become less accurate in large spaces where Lidar or RGB-D have long travel distances) and reduce the computational burden of SLAM (which might result in deployment of less expensive hardware). To this end, the fundamental tradeoffs will be identified on the requirements both on the type and nature of the sensors embedded or installed on the robot and on the environment. IMU will be considered for dead reckoning, cameras for a line or feature following and wheels encoders. Moreover, the use of RSSI measurements will be investigated (existing Wi-Fi beacons or deploy BLE or UWB). Ideally, only onboard sensors will be utilized and, thus, minimize installation time of ENDORSE system. However, alternative solutions, using barcodes or QR codes on the wall in well-chosen areas, will also be deployed, to make localization easier for the case of docking.

As the indoor localization and mapping are concerned, effective data fusion and state estimation algorithms for indoor robust localization and mapping-update in the actual environment will be developed. Standard state estimation algorithms usually show weak performance in the presence of data outliers, systematic errors and invalid model assumption. Advanced algorithms for global localization, that operate efficiently with sparse asynchronous and heterogeneous measurements will be developed while being robust to the presence of non-consistent measurements, inaccuracy in environment modeling, and drift and inaccuracy in the robot evolution model. After the integration and simulation, a robust state estimation in the presence

of data outliers, specifically for indoor human/robot localization tracking, will be held. The approaches will be adapted and extended to localization and mapping update.

Electronic Health Records

The European Union identified the development of eHealth ('eHealth Action Plan 2012-2020: Innovative healthcare for the 21st century', 2012) and mHealth ('Green Paper on mobile health ("mHealth")', 2014) systems and services as a top priority for the advancement of the quality of healthcare provision, leading to the advancement of patients' quality of life, while saving significant healthcare expenditures. Placing the citizen at the center of innovations, the development of cloud-based EHR systems, facilitating the complete patient's medical history, will allow medical experts for more informed, timely decisions, hence advancing the level of current clinical practice.

For achieving such a radical transformation, it is essential for different healthcare systems to be able to communicate and share information. In other words, install the necessary interoperability mechanisms that will allow medical experts from different specialties, practising medicine in different hospitals, and using different systems, to connect to a patient's EHR and update it with the relevant clinical information. Towards this direction, the *European Commission Decision 2015/1302 of July 2015* recommended 27 IHE - Integrating the Healthcare Enterprise ('Integrating the Healthcare Enterprise (IHE) - IHE International', 2018) - profiles describing the different layers of interoperability at a European level, thus providing software vendors with the appropriate power to develop genuinely interoperable EHR systems for storing and sharing medical data.

Going one step further, appreciating the greater socioeconomic impact of such endeavor, the EU has acknowledged the necessity of interoperable EHR systems by incorporating them under the umbrella of the Connecting European Facility (CEF) EU instrument towards forming interconnected and trans-European digital infrastructures and networks. Currently, the ongoing CEF program for cross-border healthcare provision, simultaneously being developed in 17 member states, will facilitate the exchange of the minimum Patient Summary (PS) between countries, while accommodating electronic prescription (ePrescription) and dispensing (eDispensing) functionality, adopting the *Directive 2011/24/EU* (Joint Action to support the eHealth Network, 2016), by 2020.

Within the context of the ENDORSE project, the objective is to augment our existing EHR system (Antoniou et al., 2017; EU Project, 2017) complying with the afore-described interoperability requirements with vital signs data coming from the e-diagnostic support module detailed below. For that purpose, the necessary APIs will be developed relying on the Fast Healthcare Interoperability Resources ('Index - FHIR v3.0.1', 2018) standard, the most widely used standard for developing smartphone-based mobile health application today (Avgousti et al., 2016). Lightweight APIs will acquire data coming from different sensors, at preset sampling rates, use the suitable drivers residing in the e-diagnostic module's communication interface, and assemble them into JSON or XML like the format for communicating them to the cloud-based EHR. Naturally, the appropriate security and device authentication procedures will be installed, while the EHR system will facilitate appropriate auditing schemas for registering each communication and data update session. The latter functionality will rely on accumulated experience from FISTAR (future internet for social and technological alignment) and resulting FIWARE specific enablers that were previously developed. Additional EHR system functionality will allow generating relevant reporting documents, will accommodate statistical analysis, and support export features for further data analytics purposes.

Diagnostic Support Module

As previously explained, the diagnostic support module will be mounted on the robot chassis allowing the overall robot to become an e-diagnostic mobile station. Equipped with a set of non-invasive sensors/devices (ECG, blood pressure, oximeter, temperature), this mobile station will then make possible medical exams, generate diagnostic reports and securely forward them to the patient's cloud-based EHR. This module will have to be easily pluggable and benefit from all the existing interfaces available on the robot that are necessary to its use.

Why this module?

The current finding in the hospital is that numerous trolleys or carts with medical devices are disseminated in every corridor of the building, often left alone without any supervision. Nurses are losing time searching for them, and this can, unfortunately, happen when they need it urgently. Another risk is that patients having easy and free access to medical devices on the trolleys can increase the risk of equipment's deterioration or degradation.

The e-Diagnostic module brings the first answer to this problem gathering in one place and at the right moment, all the necessary medical equipment a nurse could need for a medical check-up. Another asset is that all the embedded sensors in the module are already powered on and can be used immediately, which is not the case when all the medical devices are left on a trolley. As all the patients' medical data are instantly sent to a cloud-based server, this also limits human mistakes or loss of papers. The e-Diagnostic module offers a real service innovation providing several advantages regarding:

- **Organizational impact:** the robot moves up to the medical caller (nurses, doctors) and not the opposite. The e-health module information collection provides diagnostic assistance for healthcare professionals, enabling faster and more efficient management of patients in all circumstances while optimizing the use of specialized human resources.
- **Economic impact:** All hospitals have budget constraints. Instead of buying multiple medical devices for the same service, the e-Diagnostic module gathers all of them in one place allowing thus a gain of time and money.
- **Human impact:** Days are already quite long and tedious in a hospital for medical staff having to run everywhere to find their tools. The e-Diagnostic module brings simplicity and less physical stress as it moves up to the requester when called.

How will it come?

A possible architecture for the diagnostic support module is a pluggable device powered by the robot. This device will consist of a set of non-invasive medical sensors connected to a supervising unit. This unit will be in charge of managing and handling the sensors but also serves as a preprocessor for the medical data and a gateway to the patient's cloud-based EHR. As the robot already features a communication interface, the supervising unit should be able to use this interface to transmit diagnostic reports to the cloud-based EHR. This whole architecture is illustrated in the following block diagram:

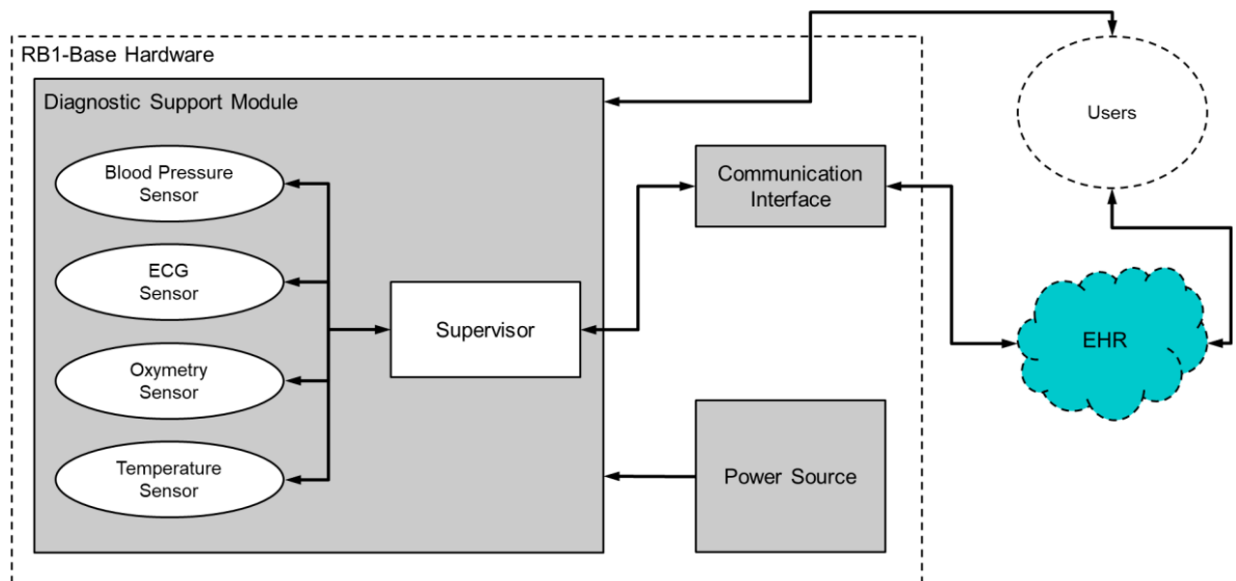


Figure 3: The overall architecture of the ENDORSE system

The architecture can be divided into three global subsystems:

- Acquisition: a medical data acquisition module represented by its sensors and the supervisor
- Communication: a communication module represented by heterogeneous networks both intrinsic to the sensors and more generally between the various components of the system.
- Consultation: a consultation module for analysis and diagnosis of results

FUTURE RESEARCH DIRECTIONS

ENDORSE is an ongoing EU project, with a 3-year time frame, ending in September 2021. During this period, it is expected to address several challenging aspects of the use of indoor logistic robots in hospital environments. More specifically ENDORSE will: a) compare the utilization of robots in commercial spaces with their use in other fields, such as warehouses (e.g. Amazon is using robots extensively to handle orders) and, thus, acquire know-how and useful lessons. A comparison of these two environments, a warehouse, where there are no people, and a commercial space (potentially a hospital), where human presence is dense, would be of great interest and could reveal robot navigation issues. b) estimate the economics of the application of robots in hospitals. A 500-beds hospital requires more than 850 person-hours per week, which is translated to more than 10 million € per year (depending on the implementation country), as it was mentioned in the introduction. However, this should be evaluated in comparison with the cost of acquisition and ownership of the robots as well as an expected improvement in the quality of services. c) investigate the safety of both the transported items and the professionals, as well as the accurate and on-time delivery.

CONCLUSION

The implementation of this project in the Marie Skłodowska-Curie Action (MSCA) - Research and Innovation Staff Exchange framework (RISE) Horizon 2020, will be a great opportunity to exchange knowledge, know-how and experience between the SMEs and creative academic groups of the ENDORSE consortium with the ultimate goal of successful business, thanks to a challenging R&D project that intends to address one of the major topics in the industry in general and the health care provision in particular: The Human Robot Interfaces. Regarding future work, the defined research strategy will be carried out in order to accomplish the project's objectives and identify the methods to be used in it. The outcomes of the ENDORSE project will offer them more visibility in Europe but also worldwide, offering them undoubtedly new career perspectives and horizon.

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