Advances in Robotics Research, *Vol. 2, No. 1 (2018) 59-68*
DOI: https://doi.org/10.12989/arr.2018.2.1.059

Essential technical and intellectual abilities for autonomous mobile service medical robots

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(Received December 25, 2017, Revised February 6, 2018, Accepted February 22, 2018)

Abstract. Autonomous mobile service medical robots (AMSMRs) are one of the promising developments in contemporary medical robotics. In this study, we consider the essential technical and intellectual abilities needed by AMSMRs. Based on expert analysis of the behavior exhibited by AMSMRs in clinics under basic scenarios, these robots can be classified as intellectual dynamic systems acting according to a situation in a multi-object and multi-agent environment. An AMSMR should identify different objects that define the presented territory (rooms and paths), different objects between and inside rooms (doors, tables, and beds, among others), and other robots. They should also identify the means for interacting with these objects, people and their speech, different information for communication, and small objects for transportation. These are included in the minimum set required to form the internal world model in an AMSMR. Recognizing door handles and opening doors are some of the most difficult problems for contemporary AMSMRs. The ability to recognize the meaning of human speech and actions and to assist them effectively are other problems that need solutions. These unresolved issues indicate that AMSMRs will need to pass through some learning and training programs before starting real work in hospitals.

Keywords: medical robot; service; intellectual abilities; technical requirements; internal world model

1. Introduction

The field of medicine involves a considerable number of routine transportation, information, and other auxiliary service procedures. Therefore, autonomous mobile service medical robots (AMSMRs) are one of the most promising developments in contemporary medical robotics (Wang *et al*. 2006, Butter *et al.* 2008, Rogatkin *et al*. 2013, Ciupe *et al*. 2014). The first AMSMR, named "AMS-car" appeared in the mid-1970s at the Inova Fairfax Hospital, USA, and it was used to move containers with food trays to patients. At present, there are several articles in journals as well as on the Internet devoted to different AMSMRs in clinics including the robot "HelpMate"-the world's first powerful transport service robot for the delivery of different drugs, analyses,

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http://www.techno-press.org/?journal=arr&subpage=7 ISSN: 2287-4976 (Print), 2287-4984 (Online)

materials, and documents inside a hospital, functioning round the clock (Evans 1994). The subsequent development of these ideas led to the creation of the “TUG” and “Hospi” series of robots. There are several such robots in clinics, and they have the ability to communicate with people and autonomously navigate and move around any room-type space. This is a good option for automating logistics in new or expanding hospitals.

In addition, Russian robot “R-Bot” for telepresence (www.rbot.ru), remote-presence robots such as “RP-7,” “RP-8,” and others, which are information robot-manipulators allowing oral and visual doctor-patient communication (Wang *et al.* 2006), and many other similar projects are well-known. The last generation of the “RP” robot family - robots of the “RP-VITA” series - was approved by the FDA in 2013, leading to its introduction into hospitals. The “RP-VITA” robots can move around the clinic and find the required room and a patient’s bed without human intervention. A doctor must only direct the robot to carry out a task by pressing the corresponding button.

However, there have not been any general methodical manuals and rules for engineers describing how to create such smart machines so far. Owing to the complex problem of creating intelligent robots, autonomous smart AMSMRs do not exist in hospitals yet. Today, all known medical robots, including “RP-VITA” robots, are rather manipulators or programmed automatons than autonomous smart machines. They are not very effective in clinics currently, hence, their production scale and sales are not very high. Today, not more than thousands of such robots work in hospitals all over the world, although there is a need for millions.

We believe that this situation arose due to the lack of proper analysis of necessary robotic functions in hospitals as well as the lack of a common engineering theory for such robots. How to create them? With what to start the development first: hardware or software?

The main objective of this theoretical study is to formulate scientifically justified hardware and software requirements, to hardware and software in order to build such AMSMRs to make them helpful for both staff and patients in hospitals. We are not a team of robot manufacturers or developers. We are a scientific team at a medical research institute and hospital. Therefore, our main goal was to study two problems:

i) Identifying robots with the appropriate hardware and software solutions that can be bought and effectively used in our clinics at present, i.e., understanding which AMSMRs we require exactly.

ii) Identifying such robots on the market and deciding whether we should buy them now or wait and participate in their development?

After a short introduction in section 1, the basic concept (scenario) of an AMSMR functioning in hospitals is considered in section 2. Based on our inferences, the required technical and intellectual abilities to fulfill the concept are described in sections 3 and 4.

2. Functional duty of AMSMRs in hospitals

At the initial stage of our study, we interviewed medical staff and patients of different departments of a multi-clinical and multi-functional medical research center, “MONIKI,” to receive a verbal description of the most prospective applications for AMSMRs in the healthcare system. The interview was conducted using the research interviewing method in the form of a semi-structured short conversation (Kvale 1996). We interviewed 24 participants, including two surgeons, three therapists, one radiologist, three nurses, three clinical department heads, eight patients of these departments, and four visitors. The main issues discussed were: How are the actions of robots conceived in their clinical department? For what purposes and in what situations are they relevant? Then, all interviews were generalized and analyzed by the method of the expert assessment (Rogatkin *et al.* 2015a).

In addition, we imitated and simulated different situations by means of a mental experiment to substantiate various options for the robot's roles and actions. Some simulated examples of AMSMRs functioning in hospital are as follows:

Example 1: Doctor orders an AMSMR to find the patient N on the hospital’s premises and to inform the patient about a new stage of treatment commencing next morning. The robot knows where the patient’s bed and ward, so it goes to the patient’s room but does not find the patient there. The patient is temporarily out. The robot makes a short detour round the territory to find the patient. The AMSMR uses the probability approach, determining where the patient can be now with the maximum probability. Additionally, on its way, the AMSMR asks other people whether they know about the patient’s location. After all these, the AMSMR finds the patient in a lounge, for example. Then, the AMSMR starts a verbal contact with the patient and informs the patient about the new treatment procedure and how it would benefit the patient.

Example 2: Doctor must give some information and confidential documents to another doctor before going on a summer holiday. However, the other doctor is absent on the present day and will be at work only the next morning. The first doctor tells the robot to complete the job instead of him and puts the documents in one of the drawers inside the AMSMR, like in a safe box. The next morning the robot finds the required recipient. The AMSMR explains the mission to the recipient doctor, gives all the verbal information required, and opens the drawer. If the desired recipient is absent the next morning as well, the AMSMR repeats its search for the doctor every N hours until it finds the doctor. Before this moment, the AMSMR does not tell anyone about the mission. Nobody can open the drawer but the designated recipient.

Example 3: On the duty-post in front of the entrance/exit of a certain department in a hospital, a team of robots meets and observes incoming/outgoing people. A new visitor comes and wants to visit his friend N. The master robot orders the slave robot to accompany the visitor to his friend, to find this friend, and to make sure that they really know each other. The slave-robot guides the visitor as required and ensures safety by asking the patient of the acquaintance and understanding the answer presented. If the patient is absent and is not in the designated room, the AMSMR assists the visitor to find the patient on the hospital’s premises as described in the Example 1.

The interview analysis, in addition to the telepresence (remote-presence) function or a transportation function, which are often mentioned in publications as the main useful function for AMSMRs, helped us to determine the following prospective tasks, which can be solved with the assistance of AMSMRs:

-Performing an interactive lecture-excursion (10-15 min) for patients, on admission to the hospital, about the daily routine involved, the building plan, and more.

-Informing patients about the time of diagnostic and (or) treatment procedures, repeated reminders about it starting 15-20 min before the scheduled time on the scheduled day.

-Searching for the patient in clinics, for a required patient, physician, or (and) a nurse, to inform them about concrete instructions, problems, including urgent ones.

-Delivering small private things, documents, etc. to patients or medical staff in their wards (rooms) and back, saving these things and documents for the given recipient.

-Listening (with a recording) to a patient’s call, requirements and complaints, and passing this information to medical personnel.

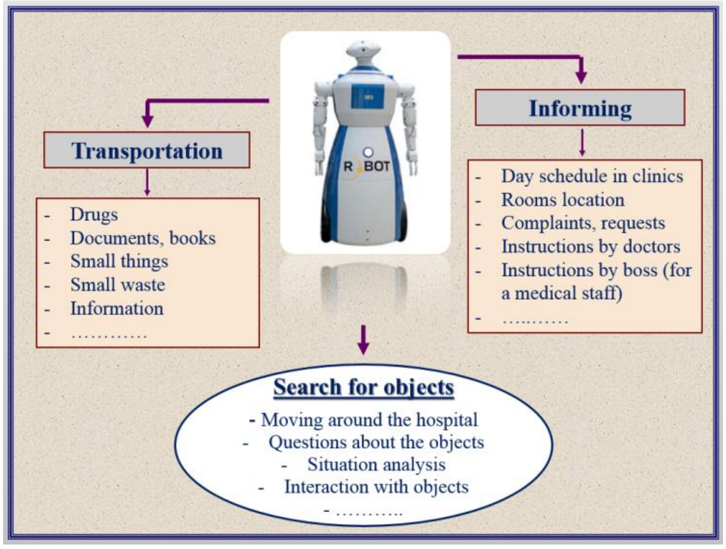

Fig. 1 Functional duties of an AMSMR in hospitals

-Monitoring the presence of unknown objects/people on clinic premises.

It becomes clear from the list above, that the vast majority of prospective scenarios for AMSMRs is associated with transport as well as with information and (or) searching tasks within the limits of the room-type territory (Fig. 1). In addition, some security tasks can be entrusted to an AMSMR. AMSMRs are needed in hospitals to implement a quite compact and unified set of simple instructions, such as to implement different errands associated with seeking an object of interest, interacting with different objects, delivering objects, receiving and storing the information from people, and processing as well as transmitting this information to other people. All these functional duties of AMSMRs (service and assistant functions) appeared to be common for most departments of a typical hospital. Therefore, they might be general duties for a typical and universal AMSMR.

It makes the generalized task of the AMSMR functioning a finite one, limited (restricted) both in physical building space and in the space of possible decisions and actions. It also makes it of a closed type, that is, all possible situations and methods of their resolution can be described exhaustively in the closed form. It allows us to illustrate all main functional duties for an AMSMR as shown in Fig. 1.

To perform all these functions, an AMSMR needs to have the corresponding hardware and software.

3. Required technical abilities (hardware)

Detailed analysis shows that an AMSMR should consist of a mobile platform, which has attached sensors, at least one arm (a mechanical unit) to operate with doors and an audio/visual interface to interact with people/robots. It should have some drawers, such as box-like storage compartments, that are made to slide horizontally in and out of a robot’s chest, which are intended for transportation of small items. All this determines the generalized structure of an AMSMR as shown in Fig. 2.

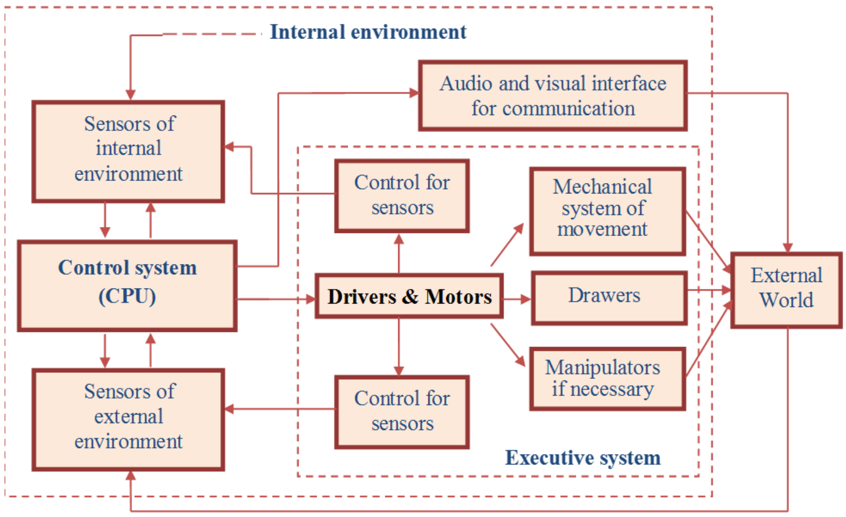

Fig. 2 Generalized structure of the AMSMR hardware

One of the most complicated problems is a manipulator (unit) to open doors. It is possible to adapt the environment by constructing doors for automatic opening by external commands. However, there will not be an autonomous robot acting independently in this case. It will depend on external equipment and their functionality. Furthermore, the cost of such a solution in existing hospitals can be too high. Therefore, the most universal and cheap solution for this problem is a manipulator on a mobile platform available to open all doors. Today, there is a standard use of door handles in the form of a swivel lever in hospitals; so the universal solution for the problem exists.

Along with this, the other electro-mechanical hardware is typical for all mobile robots: motors, odometry sensors, distance meters, rechargeable battery, and more. With no need to describe these in detail here, it makes more sense to elaborate on aspects such as the speed of robot movement and battery capabilities.

The movement of the robot inside a hospital should be no faster than 1 km/h in the general case to avoid any accident. In the dangerous or urgent situation, the speed can be increased to 2-3 km/h but not more. The useful period of robot action between battery recharges should be no less than 8 h. However, in the case of extreme danger, even after 8 h of hard work, each robot should be able to act for 1-2 h more without recharging. To achieve this level of complete autonomous functioning, the robot should automatically find the place to recharge. Hence, such place should be specially equipped and marked.

Very important and needful structural block of the AMSMR's hardware is the interface for human-robot communication. For mobile autonomous service robots, especially the medical ones, there should no longer be a question of humans controlling a robot, but of an equal interaction and communication between people and a robot, especially when the robot solves different problems in the external world. The most widespread and powerful interface for such a communication is the mutual-modalities interface. This offers various options for audio and visual interactions. Multimodality means the possibility of both manual and automatic input and output of various textual and graphic information. For example, reference data (data of type "Help") on the interactive screen of the robot monitor and parallel analysis of incoming visual and voice messages to the robot, voice prompts, questions and references using a speech synthesis, and the analysis system. This seems to be the most promising prospect for AMSMRs, as elderly people and people with diseases of the eyes or ears can visit hospitals and be given a wide variety of choice as regards alternative ways of communication. This can include a possibility of communicating with a completely blind person. Accordingly, the developed AMSMR interface should contain all these capabilities and technical components for their implementation.

Table 1 Main required intellectual abilities by AMSMRs

No.	Interaction with	If known	If unknown
1	Territory (rooms, passes)	Determining the current location; planning the path; avoiding obstacles; opening doors	Mapping; incorporating new data in the internal WM database; opening doors
2	Furniture, other objects	Recognizing the object to interact; recognizing whether the object belongs to the person (robot); determining whether the object is an obstacle and if it is, then whether is it movable (like a door) or not (like a cupboard); planning effective procedures to successfully interact (to remove, to bypass, to search for a patient inside (if on bed))	Classifying one of the known type of objects; if impossible, then sounding an alarm; determining whether an object belongs to the person (robot); determining friendly or dangerous objects and if friendly, incorporating new data in the internal WM, else sounding an alarm
3	People	Recognizing the person to interact with; recognizing a doctor/nurse/patient; exchanging information (if necessary); recognizing orders (commands); exchanging small items (if necessary); performing actions by commands; prioritizing these commands	Determining friendly or dangerous and, if friendly, incorporating new data in the internal WM, else sounding an alarm
4	Other robots	Recognizing the robot to interact with; exchanging information (if necessary), which includes commands and data; validating the necessity and correctness of such an exchange; determining the situation master/slave; considering teamwork	Determining friendly or dangerous and if friendly, incorporating new data in the internal WM, else sounding an alarm
5	Small items	Recognizing the thing to interact with; recognizing the thing belonging to the person (robot); determining the thing's dimensions, to check if it is possible to be located and transported in drawers	Classifying the thing into one of the known type of things; determining whether the thing belongs to the person (robot) and if not, then sounding an alarm, then alarm
6	Itself	Prioritizing actions; planning actions; evaluating the possibility to act in a given situation; evaluating the battery charge and health of the internal "organs" (blocks, units) to act	Not applicable

4. Required intellectual abilities (software)

Based on the expert analysis of basic scenarios of the behavior exhibited by AMSMRs in clinics, such robots can be classified as intellectual dynamic systems acting according to a situation in a multi-agent environment. To follow the scenario in full-scale, AMSMRs must have a well-developed model of our real world-the internal world model (WM). AMSMRs should identify different objects of a given territory (rooms, doors, door handles), people, their speech, other robots, and small items for transportation. One of the most difficult problems is a recognition of door handles and both hardware and software resources employed to open the doors effectively. Other required abilities include the ability to recognize the meaning of human speech and human actions to assist them in a complete manner. It proves that an AMSMR will need to pass through some learning and training programs before starting their real work in hospitals. As it is impossible to construct artificial intelligence without learning (Russel *et al*. 2003, Rogatkin *et al*. 2015b), the learning abilities should be included in the AMSMR software as the basic function.

Mental experiments and simulation of both typical situations and ad hoc scenarios of AMSMR behavior in clinics allow our team to formulate the set of required intellectual abilities for their implementation in different situations. It is important to note that any intellectual abilities are used and are necessary only if the interaction with the external environment and (or) external objects (subjects) is expected or exists. Therefore, all required intellectual abilities can be classified according to different types of interactions, as shown schematically in Table 1. They can differ if a known or unknown object (subject, item) comes up to interact; therefore, one of the basic AMSMR intellectual abilities should be to determine and differentiate among known/unknown objects (subjects, items) within the view of the robot. This differentiation stems from the checking procedure, during which the robot estimates whether this object (subject, item) is included in the robot's internal WM or not. If not, the ability to upgrade the WM should exist as well.

Special importance of human recognition appears in many security tasks. For example, consider transferring documents to a specific recipient, like the scenario described in Example 2 in section 2. The ability to recognize an attempt of unauthorized access is required here, as well.

Besides objects, the WM of an AMSMR should store a history of interactions with other specific objects. For example, the history of distributed things and the information exchange between people. To interact with objects, it is necessary to recognize their functional state. For example, whether the patient is asleep or not, whether the door is opened or closed, whether the object is moving or stays motionless, and so on.

Generally, the internal WM of an AMSMR should not only involve a structuralized set of categories (objects) of the environment and their physical characteristics for recognition but also should have all means of describing possible semantic associations among all objects. This could extend into describing their possible functional state, their history of movements, their possible interrelations as well as the rules of such interrelations, and more.

All these determine the needed structure of the WM. It must include, in addition to physical models of external objects (rooms, furniture), some general non-object and procedural (functional) terms: way, distance, trajectory, direction, motion, belonging to a man, and so on. The AMSMR model itself should be the important element of the WM. It should allow a robot to determine itself as the key element (object) of the world, to enable it to move, communicate with other objects, and simultaneously (in a certain way), as a special "subject" of the world. This would mean the impossibility to ordinarily communicate with itself (with the object "I am") like with other objects.

For example, it is impossible and senselessly to search for itself. All these require some models of the robot's "physical" and "analytical" opportunities in the WM.

Today, a number of approaches are known to form such a WM for autonomous mobile robots (Roth *et al.* 2003, Burgard *et al.* 2008, Elfring *et al.* 2013). However, the overwhelming majority of such a WM is de facto a simple geometrical description of the territory map and the objects' location in the indoor environment (Kułakowski *et al*. 2010). They describe a statistical panorama (situation) of the territory, but tell nothing about the history, logic, and possible ways of developing the current situation in time. Such a WM is definitely needed, but it is only one of the elements in the required, large-scale, effective, and workable WM for an AMSMR.

Some publications (Burgard *et al*. 2008, Elfring *et al*. 2013) indicate that a set of special semantic attributes of objects describing sense (semantic) associations between all objects are needed to create a full workable WM. In our opinion, a WM presented by B. Coltin *et al*. (Coltin *et al*. 2010), is closest to the required WM for smart AMSMR.

The model by B. Coltin *et al*. offers a modeling approach that differentiates among the motion models of different objects in terms of their dynamics, namely: the static landmarks (for example, goal posts, lines, corners), the passive moving ball, and the controlled moving robots, both teammates and adversaries. In their article, a WM is a tuple {O, X, S, M, H, U}, where: O is the set of labels of objects in the world, X is the set of possible object states, S is the set of possible sensor readings, M is the set of models of the objects, H: MxO→X is a hypothesis function that returns the current state of an object, U: MxOxS→M is the model update function. The perception of the state of the world by the robot using such a WM is completed today, but, unfortunately, this WM is restricted by the objects of the football-playing situation only (Meriçli1 *et al*. 2011). It is based on the concrete football-game data of a robot's sensors (tuple S); therefore, it is not widely applicable for AMSMRs. AMSMRs need their own, special WM. Therefore, the problem of developing and forming such a WM is one of the key problems on the way of incorporating AMSMRs into hospitals.

Our hypothesis is: for the problem of such mobile information/transport service medical robots, the closed-form and limited character of the WM can be proven. Indirect evidence of this hypothesis can be obtained by means of specifying all objects and their properties, including functional properties within a hospital. It takes time and a detailed description, which is too cumbersome to print it completely in this article, but it is possible. Anyone can make sure on their own that there are not so many variants of things, objects, and events in clinics, as it may seem at a glance.

5. Conclusions

We tried to develop a formal and scientific approach for substantiation of technical and intellectual abilities for AMSMRs from first principles. Until now, smart, intellectual AMSMRs do not exist in our hospitals due to the complex problem of creating such intelligent machines. At present, there are not any general methodical manuals and rules for engineers on how to create such AMSMRs. What should be done as the first step on this way? Should we create the hardware or the software first? In fact, this unstudied situation is one of the key reasons that prevents the worldwide usage of robots as daily service machines (Mastrogiovanni and Chong 2013).

The expert analysis of basic scenarios of the behavior exhibited by AMSMR enabled a classification of such robots as intellectual dynamic systems acting according to a situation in a multi-agent environment. AMSMRs are expected in clinics to implement different errands associated with, mainly, seeking an object of interest, interacting with it, receiving and storing information from people, and processing and transmitting information to other people. To perform such functions, AMSMRs first need corresponding hardware. Detailed analysis demonstrated that AMSMRs require a mobile platform, with attached sensors, at least one mechanical unit (arm) to operate doors, and an audio/visual interface to interact with people. They should also have some drawers (box-like storage compartments) that are made to horizontally slide in and out of a robot's chest, which are intended for the transportation of small items.

The study also demonstrated that to replicate basic scenarios on a large scale, such robots must have a well-developed model of our world (the WM). AMSMRs should be able to identify different objects of a given territory (rooms, doors, and door handles), people, their speech, other robots, information to communicate, and small items to be transported. One of the most complex problems is recognizing door handles and both hardware and software resources to open the doors effectively. The ability to recognize the meaning of human speech and human actions to fully assist them is also required. As it is impossible to construct artificial intelligence without learning, the learning ability should be included in AMSMR software as the basic requirement. Then, any intellectual abilities become necessary only if the interaction with the external environment and/or external objects is expected or exists. Therefore, all required abilities can be classified according to different types of interactions. Such a classification was formulated in this study. It formally described the functional requirements to a robot's software and the WM, which assisted to create the WM in the closed form.

Acknowledgements

The research described in this paper was financially supported by the Ministry of Investments and Innovations of Moscow Region (RF). As a continuation of the research, it is possible to collaborate with any manufacturers or developers of AMSMR all over the world to implement the similar approach in real machines and to test any AMSMRs in real clinical environments on the base of laboratory of medical and physics research in Moscow Regional Research and Clinical Institute "MONIKI" named after M.F. Vladimirskiy (www.medphyslab.com).

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