Analysis and design in providing a robotised cleaning and validation system for hospital environment

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Abstract— **Health care and hospitals services could greatly benefit from technological innovations in many fields beyond the disease treatment itself. For instance the cleaning process deserves a significant role among the services that a hospital must deliver. In this study we explore the fully automated and the traditional (human-based) cleaning protocol, we define its main components and discuss steps and benefits in the introduction of a partially automated solution based on a new robotic system.**

Keywords- Robotics, Cleaning services, Protocol Optimisation, Hospital

I. INTRODUCTION

Activities performed by humans have always been affected by innovations, such as the introduction of automation processes. Health care and hospitals greatly benefited from all these innovations, leading to a far greater awareness of the medical possibilities in treating diseases. However, the quality of health services is definitely more than just the medical aspects and the cleaning process deserves a significant role among the services that a hospital must deliver. This service, being still mostly manual, shows some criticalities that could be overcome by introducing a system with a higher level of automation.

Cleaning is a process composed by different tasks; essentially we identify two sub-processes: the cleaning activity itself and the verification of its effectiveness (cleanliness verification task). Given the current available technologies, introducing an automated cleaning system is still an uneconomical option; the inefficiency of the robots leads to a condition where costs are higher than benefits. On the other hand, designing and introducing an automated cleanliness verification system is a viable option.

Therefore, we argue that the cleanliness verification system can be introduced in a short term perspective, while the cleaning system itself only in a long term one. Accordingly, we focused on two core issues:

(i) the cleaning task in the long term, which focuses on the organisation and the sizing of a swarm group of robots;

(ii) the verification task in the short term, which focuses on the issues related to navigation and measurement of the cleanliness.

The cleaning task requires a system composed by simple automated units cooperating together, whose control system represents the critical issue. The cleanliness verification task may be performed by single automated units, through the adoption of simple positioning and moving methods and of basic sampling systems.

In the following Section 2 we start exploring the cleaning problems in a hospital. This chapter is based on a scenario developed with the San Raffaele Hospital (HSR) in Milan.

In Section 3 we recall the available automation and robotics technologies and propose our scenarios for solutions. Two solutions are devised: a short term one, where only the certification of cleaning is robotised and a long term one, where the cleaning itself is robotised.

In Section 4 we technically devise methods that could exploit robots to ensure almost full, verified coverage and methods to verify the sanitisation condition and to support the periodic control of the cleanliness.

In the Conclusion section we discuss about how to assess the sustainability of the solution and the consequent practical benefits.

II. APPROACHING THE CLEANING PROBLEM IN A HOSPITAL

The hospital is a complex institution. There are many problems and criticalities that are not exclusively related to medical aspects, such as the handling of objects (e.g. drugs and meals), the moving of patients, the transmission of data and the cleaning process. Among these, in accordance to the needs of our main stakeholders, we chose to innovate the cleaning process by studying the introduction of an automated system for the floor cleaning with a multidisciplinary approach.

Every day many people (patients, relatives, doctors and other workers) enter and exit hospitals. Patients under medical treatment and often with weakened immunity or contagious diseases, could be prone to infections. Hence, cleanliness deserves a special attention in hospital environments and any discussion involving it must deal with many different dimensions: economical, environmental, social, health and quality of service.

Most cleaning tools are driven by the operator who has complete control and is personally responsible for the result.

 ISBN: 978-1-61208-215-8

The most common machines are the vacuum cleaner, the washer-drier, the applicator machine and the wet vacuum cleaner, usually all of them operated by humans. There is not a big difference between devices used in hospitals or in other contexts, besides the products that are chosen as detergents and disinfectants.

There are many actions that could be taken to improve the situation from the points of view:

- economical: saving on materials, chemicals and on working time required by humans;
- environmental: optimising the dosage of chemicals, favouring green solutions;
- social: making dangerous and low-qualification jobs unnecessary, such as the janitorial services, in order to promote the creation of high-qualification jobs;
- quality: improving the cleaning system contributes to quality improvement.

Our analysis in a real hospital was possible trough a project of Alta Scuola Politecnica and the HSR. HSR has a prominent position at national and international level and it is qualified as a high specialisation hospital for the most important diseases. Some issues about the problems of cleaning and the most interesting topics emerged from meetings with HSR. It was clear from them that the entire cleaning system (route, dispensing of detergents and disinfectants, cleaning frequency) depends on the staff who is also responsible for potentially neglected tasks. There is a detailed planning of the cleaning procedures that is the guideline for operators in order to reduce processing errors. The hospital has been subdivided into areas that correspond to different levels of criticality and each of these has its own colour. This feature reflects a different cleaning protocol and the frequency in which the task must be executed. The size and the complexity of the system make the testing and the control more difficult. Specific operators perform the quality control also by visual inspection to establish the effectiveness of cleaning.

When considering automated systems, we observe that there are no examples of a completely automated cleaning system in structured environments, such as industrial buildings. Moreover we need to distinguish between two parts of the cleaning process; the cleaning task itself and the ex-post verification of its effectiveness. Accordingly, the implementation of an automated system involves two areas, in which significant improvements may be achieved: removing dirt and measure and localise the dirt.

III. The Solution Devised

Looking on the market, the cleaning machines fall in two categories: human operated or automatic. Today most of the machines for profound cleaning are industrial machines very heavy and manually driven. The automatic solutions are for small systems for home. Moreover, secondary functions as the removal of the dirt from the containers are still manual.

The analysis outcome of the described situation lead us to conclude that an automatic cleaning system cannot be proposed today in a hospital environment, both for the high costs and for the unfulfilling effectiveness. Even the use of the available automatic systems to cooperate in floor cleaning is still unfeasible and can lead to costs higher than the benefits.

On the other hand, the design and the introduction of a semi-automated cleanliness verification system is a viable option, since it needs a less complex technological platform.

Therefore, we concluded that the introduction of the cleanliness verification system can be done in the short term, while the introduction of the full cleaning system is to be done in the long term. Accordingly, we analysed these two phases of the cleaning process from two complementary perspectives: the short-term and the long-term. Our long-term solution focuses on the organisation and the sizing of a swarm of robots, while our short-term solution focuses on the issues related to navigation and measurement of the cleanliness. In devising a solution, we may say that part of the complexity and of the time of cleaning can be reduced if we exploit a team of robot for performing the floors' cleaning in hospitals.

Our vision regards an automated cleaning and validation system that is economically and socially sustainable within hospital environments that are commercially available. Hence, we do not analyse the co-building of an integrated hospital to such cleaning solutions, but we assume the feasibility constrains of current hospital structures as given and we analyse the case in which the cleaning system is introduced into an already existing building.

IV. Long Term Solution

Our long-term solution can propose a team of robots that are able to clean and at the same time verify the effectiveness and efficiency of cleaning carried out.

From this long-term perspective we developed an optimisation-based approach inspired by the work of Altshuler et al. [1], in which a multi-agent system, the swarm described by the authors, plays a central role. The swarm is defined as a decentralised group of multiple autonomous agents, that are simple and have limited capabilities. A key principle in the notion of swarms, or multi-agent robotics, is the simplicity of the agents in the aspects [3] of memory resources, sensing capabilities, computational resources. Each robot of the team does not know the global system.

Regardless of the improvement in performance, such swarm systems are usually much more adaptive, scalable and robust than those based on a single, highly capable agent, if they are properly sized.

The cleaning problem assumes a grid, partly dirt, where the dirty part is a connected region of the grid. On this dirty grid region several agents move, each having the ability to ‘clean’ the place (‘tile’, ‘pixel’ or ‘square’) it is located in, while the goal of the agents is to clean all the dirty tiles in the shortest time possible. These agents work in a dynamic environment in which a deterministic contamination spread is simulated every d time steps.

A. *Defining the number of robots*

A way to decide whether k agents can successfully carry out their cleaning task is to provide a lower bound valid for each cleaning protocol [2]. We want to find the minimal number of agents necessary in order to carry out their task

 ISBN: 978-1-61208-215-8

with a specific initial dirty area and a certain contamination spread step *d*. Due to the dynamic nature of the problem, we introduce a shape factor which takes into account that the contaminated region can change during the cleaning process. Our analysis is carried out from a mathematical and analytic point of view, starting as in [2, 3, 15, 16] with agents moving in a dirty region, each having the ability to clean the place it is located in.

The cooperative cleaners' problem has been studied by Wagner et al. [16] assuming as world model a regular grid of connected rooms (pixels), a parts of which are dirty. The dirty pixels form a connected region within the grid (matrix). Agents are able to move on this region and to clean the "dirty pixels". Due to the dynamic nature of the problem, a deterministic evolution of the environment is adopted. The goal of the agents is to clean the spreading contamination in as little time as possible.

The identification of the contamination status of the tile where the agent is located is carried out through a sensor installed on the platform. Moreover each agent is able to know the condition of tiles of the 8-Neighbours.

According to [16] we have developed a method to compute the lower bound depending on a number of parameters. This bound is plotted in Fig. 1 over the size of the contaminated region as a function of time, given an initial contaminated area (tiles), S_0 = 3000, dirty contamination spreading latency d = 3; 4; 5; 6 and different various number of cleaning agents k.

The lower bound over the cleaning time highlights the minimal time necessary for the team of robots to accomplish their job. The threshold, k_T , on the number of the agents depends on d: it is the minimum k that allows the system to complete the task in a finite time. If k is higher than k_T the objective can be reached. If k is lower than k_T the result cannot be reached even the time is infinite.

There is also an upper bound due to the fact that when the number of robots increases the probability of interference among them increases too, making it more difficult to reach the goal.

B. Defining the spreading of dirt

Those results are based on a deterministic approach regards to the contamination spread. It would be interesting to introduce a stochastic variant to enhance the dirt diffusion expression in order to make the model more realistic.

C. Defining the control policy

We can think about three different controllers for the robot cleaning system.

Firstly, a system that is activated when a human responsible decides that the hospital needs to be cleaned; the system works until the whole area is cleaned and then stops.

A second possibility is to integrate the probabilistic calculus of the diffusion of dirt into the cleaning plan. Namely, knowing when a spot has last been cleaned allows to calculate when it cannot be considered clean anymore, with a probability higher than a given threshold. In this approach we have a constantly active cleaning system and a guaranteed cleanliness level.

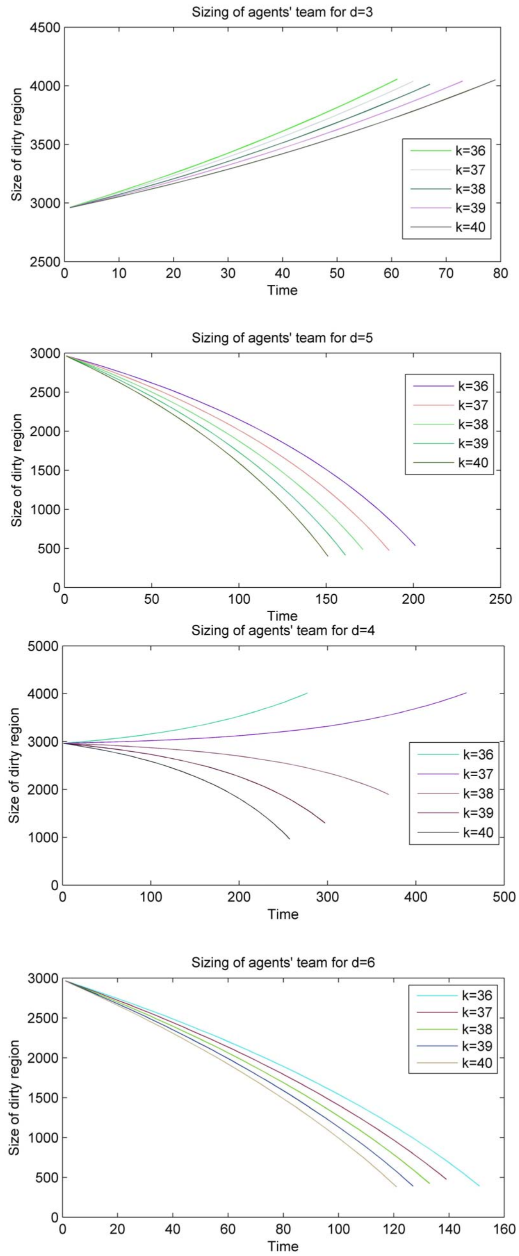

Figure 1. Evolution of the dirty region size (y axis) over the time (x axis) in function of the contamination spread step (d) and the number of cleaning agents (k). From top to bottom: given the same initial condition, each diagram presents the dynamic evolution respectively for d = 3, 4, 5 and 6; as evident, different values of the number of cleaning agents (k), in each condition, lead to accomplish the task, or to diverge from it, with different velocities. Logically the number of agent cannot grow infinitely ignoring the interference due to size and shape of the surface and agents.

A third possible approach is the integration of the cleaning system and the verification system, with verification agents that would be active at the same time as cleaning agents and that would provide them with cleanliness information: when a section is found dirty, the information is changed in real time in all the agents.

The implementation of those controllers is in the state of the art of robotics, not the construction of the real cleaning agents.

V. SHORT TERM SOLUTION

We outlined a solution for the verification system. We used a more practical approach, testing the positioning and navigation strategies as well as the methods for sampling, measuring and stocking the dirt on the floor.

The input of the navigation system is a complete map of the room and the fixed obstacles. The navigation algorithm guarantees that the robot collects dust samples in points randomly and homogeneously spread over the environment. At the same time the positioning system ensures the correctness of the sample coordinates.

A. Methods to measure cleanliness

We can divide the cleanliness measurement methods in two categories: the direct methods, applied directly to the part we are examining and the indirect methods, that require an analysis of the collected contaminants.

Different technologies support the dust investigation. The main traditional method is just visual inspection, that relies completely on human observation. Other methods measure the dirtiness in a scale using Bacharach scale (a paper that has different grey levels), or observe the movement of a drop of water (Water Break Test or Contact Angle test), or use UV spectroscopy. A simple method is the Scotch Tape Test: a strip of transparent tape is firmly pressed upon the surface, then it is displayed on an appropriate contrasting background.

On the other side we have to mention some semi-precise or precise methods that are mostly based on optical or electrochemical processes and generally require more laboratory equipment, time and cost. They are not necessary in our intended task of measuring the cleanliness of a floor. What is important is understanding whether the floor needs to be cleaned again and whether the cleaning process is performed correctly or not.

Therefore in the present work our choice is restricted to the gross verification methods. We consider the possibility to perform a deeper analysis for further certification needs. So our verification protocol is based on three main actions:

(i) take a sample of the contaminants
(ii) make the analysis
(iii) store it into the robot for further analysis.

The first analysis, more trivial but giving fast results is performed on the robot. In this case it is necessary to carefully consider the use of solvents, used in most of the indirect methods. A further problem lies in the fact that the floor should be still clean after the process. Other difficulties are related to the storage of liquids that would require a different recipient for each sample and more careful management if on board. Finally an important factor is the protocol proposed to the human resources to manage the system. Obviously one of the objectives of the proposed automation is to reduce the need of human labour compared to the current system (visual inspection, a simple method) while increasing the quality. So the automated method is expected to be more repeatable and robust than a method only dependent on human factors.

The question whether to evolve an integrated device (as a moving base) or design it ex-novo is a secondary choice. Results of our analysis show that today does not exist a device totally fulfilling our requirements, so it would be preferable considering the design of a new dedicated system.

B. Hardware equipment for the robot

Between the existing dirt investigation methods, only the principles of the Bacharach scale and the tape test (applied in an automated way) seem to be the solutions that comply with all the identified necessities.

Summarizing, the robot base has to carry an equipment composed of.

- the sampling device for the acquisition of the dirt level
- the measuring device to measure of the dirt level
- the stocking device to preserve the samples
- a battery
- motors to roll the tape

A small robot (about 50 cm in size) can move better near the obstacles. The robotic base should be equipped with sensors to detect obstacles (sonar, bumper) and encoders on the motors in order to use odometry.

The measurement is based on the tape test. An adhesive tape is rolled on two supports: on one roll there is the unused part, on the other there is the tape sector that has already passed through the measurement part. Inside each roll, there is a motor that moves it provoking the rolling/unrolling of the tape. The sampling is done by the contact of the tape with the floor. The measurement system is composed by a photodiode and a laser light source. The output consists of a series of zeros and ones: a zero means that the laser light was not able to achieve the photodiode whilst a one represents that the tape was transparent enough to allow the light to polarise the photodiode. The number of “1s” is the cleanliness level.

The sample, after the measurement, is stored, keeping a record of where the sample was taken. A tape of polytetrauoroethylene (commonly known as teflon) could be put aside the adhesive tape in the destination roll and the two tapes could be wound together. The robot keeps trace of its movement on the map and of the places where a sample has been collected.

C. Positioning and navigation

Now we focus on the choice of the positioning system. Most of the commercial robots used to clean the floor are not equipped of a positioning system, but typically use heuristic algorithms. Unfortunately this approach cannot be applied to our project. The dirt detector robot should know where it picks up each sample. From the different technologies [5] to implement a positioning system, we take odometry, computed from encoders on the wheels and the recognition of visual markers.

The navigation algorithm [5, 6] can be developed from a sequence of target points where the robot has to collect samples, using a modified version of the covering algorithms. The navigation algorithm of election for this

 ISBN: 978-1-61208-215-8

robot is map based. It is able to manage critical situations such as fixed and mobile obstacles using on board sensors.

D. Experimental proof of concept

We have developed a proof of concept of the complete navigation method using the iRobot Create [12] and the Matlab environment [14]. iRobot Create (see Fig.2) is the research-orientated version of the more popular iRobot Roomba: it has the same robotic base of it, but it is not equipped with the cleaning system. It is possible to control it with a PC using a serial communication and the Create Toolbox Interface that allows to use a Matlab real-time script to control it. There is a Simulator to test the algorithms. On the hardware side, it is equipped with different sensors (bumpers, encoders) and through the PC it is possible to connect additional external devices (as cameras).

Figure 2. Virtual rendering of the robot at Politecnico di Torino

We have added a webcam pointing to the ceiling, where we put black and white markers. The images are analysed by RoboRealm [http://www.roborealm.com]. Given the position and orientation of the markers, the information coming from RoboRealm is used to compute the position of the robot using matrix calculus. This procedure theoretically guarantees a localization error < 1 cm; also small imperfections in the camera orientation could produce an error of 5 cm in positioning.

VI. DISCUSSION AND CONCLUSION

The quality of health services is definitely more than just the medical aspects and the highest cleaning condition deserves an essential role among the services that a hospital must deliver.

A preliminary analysis shows that cleaning condition is depending on many factors, both environmental and cleaning-task-related. The environmental factors are several in number and extremely variable; this condition emphasizes the impossibility for an optimization with a "time-scheduled" managing system and leads to consider an "on–condition" decision system to be the more appropriate to manage the cleaning activity. The cleaning-task-related factors are depending on the human factor in task accomplishment, on the protocol type and on the equipment management.

The *traditional* cleaning process is still completely "human-based" (i.e. manually performed by cleaning staff). This solution implies relevant costs for the service and requires attention on protocols and verification of results to ensure health conditions both for the users and for the medical and cleaning staffs (not only dirt, but also detergents could be dangerous). The risk factors in the context of cleaning are present in all stages of the process. By the social point of view a robotised solution would improve the quality of the jobs making low-qualification ones unnecessary and improving the safety at work.

Market analysis and available technology suggest that a completely robotic cleaning system still remains an uneconomical option: the inefficiency of the robots leads costs be higher than benefits. Although robotising cleaning tasks appears to be less efficient than the *traditional* process, our analysis shows the automation of the *verification task* shall both improve the whole traditional protocol and lay the foundation for new future solutions.

A system based on a swarm of robotic agents was simulated and analysed, to reveal the most relevant characteristics and to evaluate possible novelties in cleaning protocol. Simulations show the existence of an optimised number of agents, depending on the surface characteristics and the accomplishment capabilities of each unit.

Successively the system was enhanced introducing a verification robotic unit.

This new element first implies a changing in the cleaning task management, now based on *"on–condition"* philosophy. Practically the availability of cleaning conditions data supports a new optimisation concept both for the intervention of the cleaning agents and in detergents handling and supplies. This reduced usage of the equipment leads important economic and ecological benefits.

A subsequent analysis highlighted that we obtain the same benefits by introducing the verification robotic unit also in an existent *traditional* cleaning protocol.

Today some cleaning protocols have been expressly developed to minimise the errors dues to the human factor (usually for the industrial field and somewhat dedicated to the hospital environment) but no optimisation is possible in this type of time-scheduled protocol.

Practically speaking, the cleaning process is a stand-alone task, performed far from the controller's watch. Generally a person is charged of the occasional verification task, introducing besides a further incertitude factor in the system; obviously this person isn't a cleaning-staff and (generally) he is an employ or a company manager, with a hourly rate higher than the cleaning-staff (i.e. each time-units dedicated to the verification task is more expensive than each one dedicated to the cleaning action).

In short, the introduction of the automated verification in the *traditional* process improves the system awareness and makes possible the "on-condition" optimisation.

The increased simplicity and the task automation leads to carry out more frequents checks and therefore to have more accurate data and a better knowledge of the *ambient system* and its dynamical conditions. The awareness of the real and detailed conditions allows a more incisive intervention and supports a better scheduling of the activities. The availability of new on-going data allows a continuing improvement of the protocol.

Finally, the faster discovering of anomalies and inconveniences and the improved effectiveness related to the more precise intervention, bring not only economical and ecological benefits, but also a significant enhancement of the cleaning condition.

We conclude this section with some economic considerations and a challenge for the future developments. The main outcome from our economic analyses is about the ineffectiveness and the expensiveness of the solution composed by cleaning robot agents. The immature present technology and the market conditions are the main limits preventing the success of a full-robotic cleaning stuff. Some keywords to describe these limits are: slowness in task performing, cost of energy, maintenance and productivity. Despite the estimated hourly costs are sensibly more favourable for the robotic solution (1,69 €/h) than the human-based solution (12.5 €/h), today the productivity represents an insurmountable obstacle (30 m^2/h and 400 m^2/h, respectively) and limits the interest towards this innovative solution.

ACKNOWLEDGMENT

The present work was developed within the framework of the ASP - Alta Scuola Politecnica. We thank the ASP school and faculty for the guidance and the support in project developing.

We also address a special thank to Alberto Sanna and the e-Service of HSR hospital, for the valuable introduction within the reality and the problems of the hospital environment.

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