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Design of a robotic automation system for transportation of goods in hospitals

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Abstract—**Hospitals face with heavy traffic of goods everyday, where transportation tasks are mainly carried by human. Analysis of the current situation of transportation in a typical hospital showed several transportation tasks are suitable for automation. This paper presents a system, consisting of a fleet of robot vehicles, automatic stations and smart containers for automation of transportation of goods in hospitals. Design of semi-autonomous robot vehicles, containers and stations are presented and the overall system architecture is described. Implementing such a system in an existing hospital showed the need of necessary modifications to the hospital infrastructure.**

I. INTRODUCTION

Automation is a key aspect for increasing efficiency, improving service quality and saving from both time and manpower; in environments like industrial plants, factories and offices. The basic aim of automation technologies is to replace human with machines where the tasks are generally dull, dirty or dangerous. Transportation of goods in indoor environments is one of the most essential examples for these tasks. Automatic guided vehicles (AGVs) have been successfully implemented in many factories, where the environment is rather controlled and modified easily if necessary. The advancements in robotics technology and accumulation of knowledge from the automation in industrial environments result in introducing solutions to transportation of goods in everyday places like hospitals, schools and government offices.

Hospitals are ideal candidates for the automation of transportation systems for many reasons. The highly dense traffic in hospitals requires significant amount of manpower, where common tasks are the transportation of beds, samples, food, trash, laundry, medical equipment, medical charts, office supplies and mail. Professionally educated nurses spend considerable time on these tedious tasks, which consequently affect efficiency, quality of service and costs. Therefore, successful employment of an automation system for the transportation of goods in hospitals would allow the staff to spend more time on directly patient related tasks; which as a result increase overall patient satisfaction and hospital efficiency.

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Several works has been done in terms of utilizing robotics technology in hospitals. HelpMate robot [1] is one of the earliest service robots that are commercially available. Utilizing laser range finder for localization, HelpMate is capable of reliable autonomous navigation. TUG [2] is another commercially available robot, which can transport attached charts by tugging them. Research platforms, which mainly focus on technical aspects like natural landmark based navigation [3] or implementation of two level fuzzy-logic control for navigation [4]; show that there is an increasing interest for such systems.

In this paper, it is aimed to outline the design aspects of a system which aims to automate the physical transportation tasks in hospitals. Main advantage of this system is the automated pick up and delivery of goods, utilizing stations at delivery points. Using a fleet of robotic vehicles which can be tracked and supervised by a remote server; this design provides a more general solution to the problem of logistics, rather than employing single robots or offline systems.

Rest of the paper is organized as follows. In section 2, regular transportation tasks in a hospital are briefly analyzed. Features of the overall system design are given in section 3, necessary modifications for the implementation of the system is presented section 4, and conclusions of the work are discussed in the last section.

II. Analysis of Transportation of goods in a Hospital

In order to define the problem of transportation and develop solutions for its automation; it is necessary to analyze the needs and demands, and examine the transportation systems in hospitals. In accordance to this necessity, the transportation system of Bispebjerg Hospital in Copenhagen is analyzed.

The hospital consists of 51 buildings situated in a gardenlike campus. With its capacity of 836 beds and allocated population of 255.000 inhabitants, it can be considered as a typical European medium size hospital.

The vast majority of the transport routes make use of the tunnel system which connects buildings as a network. The longest distance from one point to another in the tunnel network is approximately 1.5 km, with a total length of network exceeding 5 km. All multistorey buildings have elevators which are suitable for bulky transport, beds and carriages.

TABLE 1
ESTIMATED AMOUNT OF GOODS TO BE TRANSPORTED EVERYDAY IN BISPEBJERG HOSPITAL

Mail	500-700 kg
Laundry	3500-4000 kg
Food	2500-3000 kg
Garbage	5000-7000 kg

The majority of the daily transport consists of patients, pharmaceuticals, mail, food, items for maintenance of patients, office and general items, and garbage. Table 1 can give an overview of the scale of the heavy traffic in a regular medium sized hospital. Transportation of several other items takes place on a less frequent basis. Among the large list of various items that need to be transported in hospitals, mail can be an ideal class for automated transportation.

Mail center deals with a daily transported material of 500-700 kg, which is handled by 8 persons. Regular distribution takes place five times a day between hours 7.30-15.00, in six different routes within the hospital campus. Each route is planned such that couriers meet each other in several nodes during the rounds to exchange mail or assist each other. Rounds take about 30-50 minutes depending on the amount of material. During the first round, the couriers routinely pick up a large number of samples taken during the night and stored in refrigerators for delivery at the departments of Pathology, Microbiology and Central Laboratory.

III. SYSTEM DESIGN

Three scenarios are considered in the overall design of the system for automated transportation of goods (Fig. 1). *Shuttle* mode is the most basic mode, transporting good between two stations. *Bus* mode is an extension of the *Shuttle* mode, enabling the coverage of multiple stations in a defined route. *Taxi* mode, on the other hand, enables transportation upon request. Multiple modes of transportation can exist at the same time, enabling flexibility of the overall operation.

Overall system can be divided into hardware functions and their interconnections on one hand, and software functions and methods on the other hand. Basically, the system has three components:

1. Stations, where goods are picked up and delivered
2. Robot vehicles, which transport goods among stations
3. Containers, which encloses the goods to be transferred

Central elements in the system are robot vehicles (Fig. 2), which perform the main function of transportation of goods. An important requirement from the system is the capability to perform automatic loading and unloading of the transported goods. This leads to the necessity of designing a special container as an enclosure for goods to be transported. Stations which are capable of automatic loading and unloading containers are placed at various positions to complete the automation cycle.

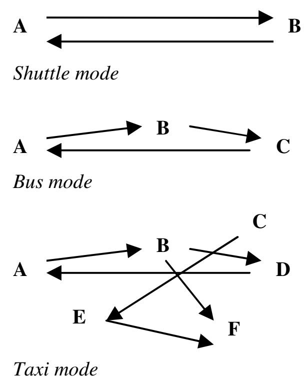

Fig. 1, Three modes of transportation. Depending on the fleet size, robot vehicles can be in different modes of transportation, in order to optimize the traffic

A. *Robot vehicle*

The vehicle is designed to move in indoor environments of a hospital. Using differential drive configuration, it is equipped with 2x200 Watts DC permanent motors with optical encoders attached to the driving wheels at the back, and a castor wheel in the front. Vehicle is intended to be operated in the velocity range of 5cm/s to 1.25m/s. Powered up by 4x12 Volt 38Ah sealed lead batteries; vehicle itself weights around 70 kg. Designed for handling various types of loads, requiring a strong mechanical base, loads up to 50 kg can be carried.

Fig. 2, Side view of the robot vehicle with the container on it

Robot control hardware is consisted of three main elements; human interface running on a tablet PC, high level control layer running on a PC104 single board computer, and low level control layer based on a 32-bit processor and servo amplifiers. High level control layer, human interface PC and the network camera, which is mainly for surveillance purposes, are connected to a local network on the robot vehicle. Using a wireless ethernet transceiver, robot is capable of connecting to the global network, enabling the remote access.

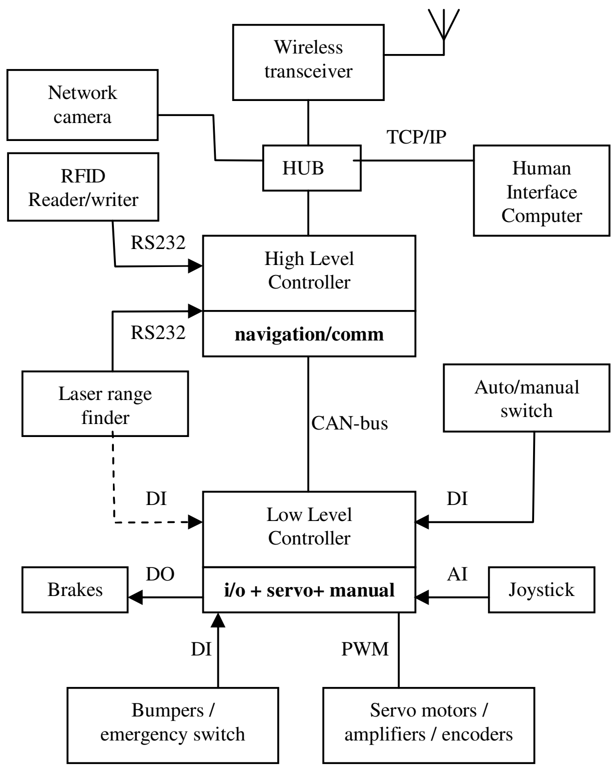

Fig. 3, Hardware system of the robot vehicle. Devices are connected to controllers with different interfaces.

Two levels of control are utilized to modularize the functionality of the robot vehicle (Fig. 3). Low level controller deals with the input-output functions, motor capabilities and manual control, whereas high level controller handles navigation tasks and communication with the supervisory system. Sensors, actuators, and other components are connected to controllers based on their functionality. Details of the control architecture are given as follows.

1) Robot low level control:

Control of actuators and interfacing analog and logical sensors take place in this layer. Equipped with an 32-bit microprocessor, this layer basically gets inputs from the high-level control module, which might be instructed by a remote server or local human interface; and deliver outputs i.e. motor commands which have to synthesize high level requests filtered by the all navigation sensors through a PID control.

2) Robot high level control

The resulting behavior of the robot vehicle i.e. transportation of goods, is basically determined in this layer of control. Users of the system can command the system through a remote access (server or station), or through the local human interface, which resides on a tablet PC. Two main function groups being handled in this layer are navigation functions and handling functions. General structure of this layer is represented in modules in Fig. 4.

Navigation functions deal with the execution of route commands given by the supervisory system. These functions can be identified as follows.

a) Routing:

Routing module receives route commands from the supervisory system. These commands are processed in such a way that the resulting path is a smooth extension of the path being followed.

b) Localization:

The robot vehicle continuously estimates its position and heading, using the odometry information provided by the low level control layer. Feng [5] defines non-systematic errors, such as uneven floors, wheel slippage, skidding or external forces, which make the information provided by wheel encoders unreliable for long ranges. In order to aid the robot to correct its position and heading, several reflectors are placed in the routes as landmarks. Ranging module detects these reflectors using the laser range finder, enabling the robot to accurately localize by triangulation.

c) Path Tracking:

This module is responsible from continuously comparing the actual position and heading provided by the ranging module, and the actual route provided by the routing module. Comparison results are used to update or compute motion setpoints that will be followed.

d) Motion Control:

Motion module acts as an interface between the low level control layer and the navigation system. In this module, motion setpoints provided by path tracking module are forwarded to, and actual position and heading information is received from low level control layer.

e) Obstacle detection:

Active area surrounding the robot vehicle is set in this module. Objects are detected and defined as obstacles, depending factors such as the speed of the robot vehicle, variance in the environment, or current task of the robot.

f) Obstacle Avoidance:

Detected obstacles, if possible, has to be avoided in order the robot to follow its path. This module computes the evasive movements needed to overcome the obstacles. Environment conditions like varying corridor width, doors or narrow passages, together with the information gathered about the detected obstacle affect the resulting evasive movement.

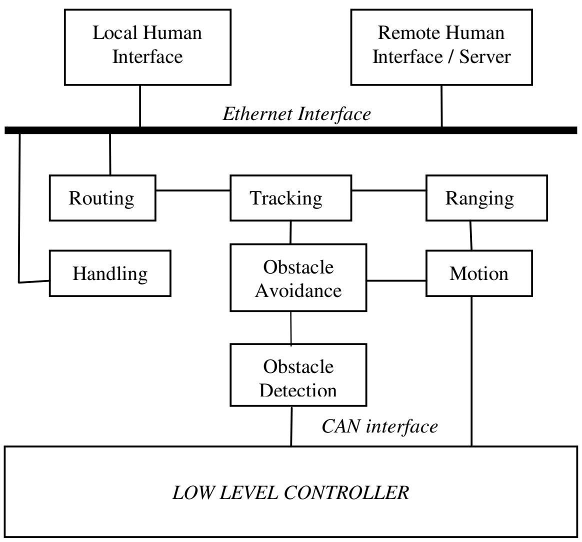

Fig. 4, High level control layer. Navigation and handling functions are constructed by modules.

The second set of functions that are handled in the high level control layer are handling functions; which are load status and load transfer functions. Handling module forwards load transfer commands issued by the supervisory system to the low level control layer, and it receives load status information.

B. Containers:

Container acts as an enclosure for the goods to be transported. Analyzing the variety of goods, their size, weight and storage conditions; a container with the size of 60x50x45 cm and the payload capacity up to 50 kg is designed. The container acts as a bay to host diverse and smaller items, including their usual cases. Lateral and top handles and lids makes it easy to handle, and enables easy access to the goods.

Security of the containers and the goods transported is an important issue. During the transportation process, the container is secured by both locking the lids, and securing the container to the robot vehicle by means of electromagnets. Therefore, the container can not be opened, or it can not be picked up from the top of the robot vehicle. In addition, every container has an embedded transponder. The robot vehicles and stations are equipped with read/write devices, enabling confidential tracking of the goods in the hospital.

C. Stations:

Loading and unloading operations take place in stationary stations, in order to make system work with a lesser degree of dependency on human presence at delivery points. The stations are used to store containers, transfer the containers to or from the robot vehicle, pick up or remove goods to or from the container by the staff, and store the robot vehicles and recharge their batteries when they are not in use.

Stations are designed to be modular, with a minimum configuration of two cells for loading/unloading and a human interface terminal (Fig. 5). More cells can be added to increase loading or unloading capacity at delivery points with high traffic density.

Each cell is equipped with a pneumatic lift system to pick up the containers or place them on the robot vehicles. Inside the station, robot vehicles deactivate the electromagnetic lock system which secures the container on the vehicle.

Fig. 5, Minimal station configuration; two loading/unloading cells and human interface.

D. Remote human interface and fleet supervision

Overall system is coordinated according to three layers of decision systems. Supervisory control system generates and combines transportation requests, assigns robot vehicles to different tasks and provide user interface to the entire transportation. Traffic control system plans the movements of goods in order to meet demanded delivery schedules and avoids possible conflicts that result from different user requests. And vehicle control system generates movement setpoints and forwards them to robot vehicles, in order to meet the planned movements of goods.

In accordance with the outlined remote human interface and fleet supervision, following briefly described function sets are intended to be implemented:

1. Transport Generation
   - Transport order initiation via human interface
   - Order execution status monitoring
   - Priority selection for transports
   - Transport task assignment to specific robot vehicle
   - Position status monitoring of the robot vehicles on the infrastructure map
   - Robot vehicle status monitoring
   - Container status monitoring
   - Container/goods tracing
   - Batch scheduling/planning
   - Event logging
   - Alarm status monitoring
2. Traffic Control
   - Display, build and modify infrastructure display
   - Planning robot vehicle movement based on transport orders
   - Routing communication between robot vehicles
   - Interfacing with external equipment(lifts, doors, etc.)
   - Make traffic control decisions based on robot vehicle requests or reported events
   - Receive position reports from robot vehicles to update or modify schedules
3. Remote User Control
   - Maneuvering of robot vehicles in maintenance mode
   - Display of the camera feeds from the CCTV infrastructure of the building
   - Display of animated navigation maps
   - Display of the sensory information of robot vehicles
   - Display of the video cameras on robot vehicles
   - Display of the diagnostic control variables on the vehicle

E. Local Human Interface

Each robot vehicle is equipped with a local human interface, based on a touch-screen tablet PC. As the supervisory system relies on the wireless link between the remote server or stations and robot vehicles, it is necessary to implement some basic operator functions locally, in case of the failure of the wireless transmission. Therefore, the robot vehicle should provide following functionality through its local human interface.

- Display alarm and/ or vehicle status
- Alarm reset or resume
- Order cancelling
- Basic vehicle movements selection
- Container loading/unloading
- Container security setting
- Voice or sound recording and play
- Priority selection of transports
- Manual selection of destination

IV. Implementation of the System

In order to test the performance of the design, the system outlined in the previous section had been partially implemented in the Bispebjerg Hospital. Most of the buildings in the hospital campus are connected by a tunnel network, which is naturally used for the paths of transportation (Fig. 6).

Being a part of the system designed, hospital infrastructure needs to be modified for implementation. Following are the main modifications made.

Wall mounted reflectors: Navigation systems of the robot vehicles are dependent on the reflectors which are placed along the corridors. These reflectors act as artificial landmarks and enable the robot vehicle to correct its position and heading, as described in the previous section. Reflecting tapes of 10 mm width and 100 mm height are placed every 2 to 4 m along the specified paths of the robot vehicles.

Wireless Ethernet: The overall system execution depends on the wireless communication between the supervisory system and robot vehicles. Wireless transmission coverage of the transportation paths is enabled by installing several wireless access points along the paths.

Automated Doors: Long corridors are often segmented by double doors in the hospital. For robot vehicles to pass through the doors on their paths, some of these doors needed to be automated by implementing standard motion detectors that are commonly used in e.g. shopping malls.

Elevators: As the robot vehicles might need to use the elevators in order to transport goods in multi-storey buildings. Robot vehicles should be able to call the elevators and command them to the desired floor. This requirement makes it necessary to modify the software of elevators, to be accessible by the supervisory system.

In addition, stations are needed to be installed at defined delivery points. Power connection, ethernet connection and pressure vessel connection for pneumatic lifts are needed for the functionality of the station.

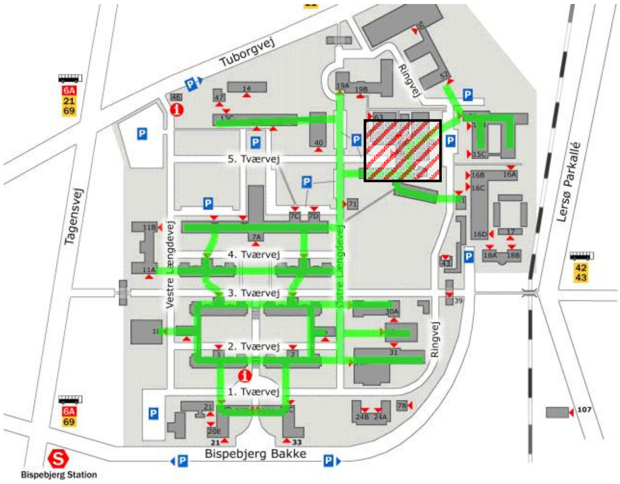

Fig. 6, Tunnel network of Bispebjerg Hospital, Copenhagen. Tunnels are represented in green. Trial tests had been conducted at north-east part of the hospital in the map.

For testing purposes, along with the modifications mentioned, a robot vehicle, a station, three containers, and a server computer had been installed at Bispebjerg Hospital. Acute Medical Attention (AMA) unit, Clinical Chemistry unit and the Mail Center are selected as delivery points for the trial system. Station was placed at the entrance of AMA. At the other delivery points, containers were loaded and unloaded manually by users.

Several trial runs had been made, in order to assess the performance of the prototype system. Robot vehicle navigation, automatic loading and unloading functionality of the station and wireless communication between robot vehicle and the system were particularly evaluated.

In addition, trials made it possible to observe and evaluate the interaction between the system and its typical users. Human interface systems had been validated, and valuable deductions had been made to improve the user performance.

V. CONCLUSION

In this paper, a system utilizing semi-autonomous robots for automation of transportation of goods in hospitals is presented. System basically consist of a fleet of robot vehicles, electronically traceable containers, stations with the capability of automated loading and unloading of containers, and a remote supervisory system which manages the transportation activity. Robot vehicles are capable of navigating autonomously, with the help of artificial landmarks placed on their paths. Containers provide a safe enclosure to the goods to be transported and increase the assets tracking capabilities. Stations are eliminating the need of human presence for loading and unloading robot vehicles.

Implementation of the prototype system to Bispebjerg hospital showed that several modifications might be needed in order to fully utilize the automated transportation system in existing hospitals, whereas most of these modifications can be regarded as a substantial general improvement of the existing infrastructures. These issues could be kept in mind while designing new hospitals.

Tests and trials demonstrated that the outlined design can be used to solve the presented problem of transportation. As a result, the level of the quality of service in hospitals can be significantly improved by utilization of such systems.

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