Safe Human-Robot Interaction in a Life Science Environment

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Abstract — In this paper we present a mobile robot assistant that is capable of safe cooperation with humans in a populated environment. The service robot assists users in biological and pharmaceutical laboratories by carrying out routine jobs such as filling and transportation of microplates. Relevant safety requirements are outlined and a safety concept is devised, which consists of various sensor systems such as laser scanners, thermographic components and artificial skin. An overview of the design of the mobile platform with a robotic arm is provided. Moreover, the approaches to object recognition and intuitive multimodal human-machine interaction using speech and touchpad input are described. All aspects are regarded concerning safety since the robot and humans share a common environment and interact closely.

Keywords: *service robotics, mobile robot, men-machine interaction, safety requirements*

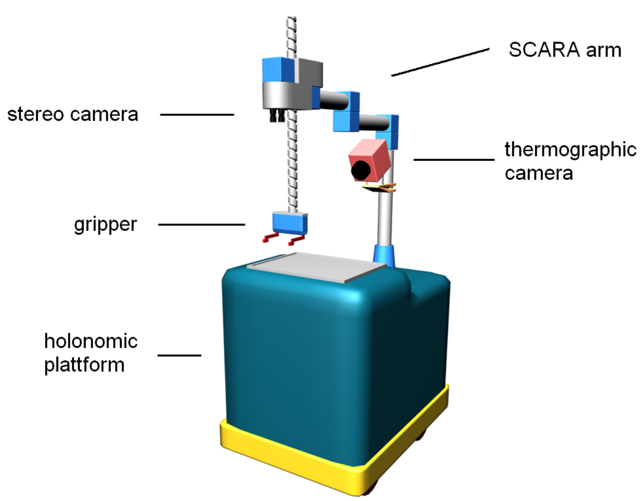


Fig. 1. Design study of the LiSA platform

I. Motivation

The field of service robotics is considered to be a growing market in the near future. Thus, many research projects are concerned with the development of robots assisting in industrial manufacturing or performing domestic work. Such robots have to accomplish many complex tasks like localization and navigation in highly dynamic environments, reliable object recognition and manipulation and natural human-robot interaction. Much progress has been made in these fields in recent years.

Another aspect in the development is often disregarded. This concerns safety requirements for riskless operation of an autonomous robot in an environment populatetd by human beings and safe men-machine interaction. The project presented here incorporates these safety aspects. The basic idea is the employment of a service robot for life science laboratories - the Life Science Assistant (LiSA). Objective is the development of a mobile service robot to interconnect laboratory equipment. Thereby, flexible automated experiment cycles are obtained, while stations can be simultaneously used for other purposes. In addition, the robot helps employees prepare experiments, e.g. by collaboratively executing transportation tasks or filling microplates. Figure 1 is a design study of the particular robot currently under development.

Previous service robotics projects such as the MORPHA Project [1] have primarily centered on fields of industrial manufacturing or domestic work. The manufacturing environment is highly structured. Human workers in this Domain are familiar with machine operation and pertinent precautions. Manufacturing and domestic settings are extremely different in this regard. A household environment is extremely dynamic. A robot operating in and interacting with this environment has to deal with various objects. At the same time, it may neither cause any damage nor harm people, even if they are careless. This makes the domestic settings impractical for service robots at present. The approach presented here is for the domain of life sciences. Life science laboratories have semistructured environments. Objects like bottles and microplates are standardized and access can easily be restricted to those who have learned to interact safely with the robot. Nonetheless, this scenario constitutes a meaningful application for using a robot, since many tasks in life sciences are monotonous, hazardous or highly sterile. This makes the LiSA scenario an ideal testbed for the consideration of safety aspects.

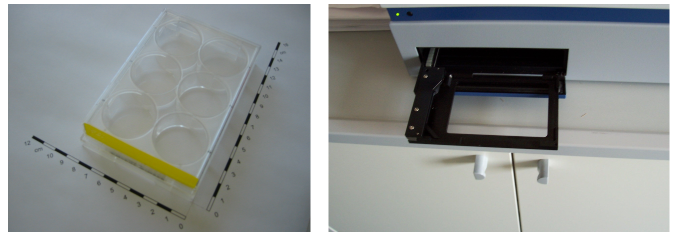
II. State of the Art and Exiting Robot Assistant Solutions

Numerous projects in recent years have aimed at developing service robots. Despite all the research done, only a few systems have become commercially available, e.g. the HelpMate robot [2] used for drug delivery in hospitals. Most systems are individual robots employed for special purposes like guiding visitors through museums [3]. Other projects have focused on user friendly interaction with robots. In general, these use natural language to communicate intuitively. Examples of such systems are the office assistant Jijo-2 [4] or the robot companion BIRON [5]. These robots have integrated spoken dialog systems but are unable to manipulate their environments. The key idea behind the research initiative MORPHA [1] was to develop service robots with capabilities to assist human users in manufacturing and health care. This project produced the robot assistants rob@work [6] and Care-O-Bot [7]. Research involved studying the interaction, collaboration and communication with human users through natural language and gestures. Fundamental safety aspects have been considered within the Care-O-Bot Project [8].

Another application for a scenario similar to that of the LiSA project is the mobile robot for automated cell cultivation developed at the University of Bielefeld [9]. A mobile robot with a manipulator takes and manages samples in a biotechnological laboratory. The project only marginally examined safety requirements and interaction with the robot.

III. LiSA-Scenario

Biological and pharmaceutical research entails a great deal of repetitive manual work, including the preparation of experiments or the loading of equipment such as drying chambers and centrifuges. Classical automation uses band conveyors or indexing tables to interconnect such units [10]. This approach has two drawbacks though. It is inflexibile and the stations do not lend themselves to use for variable experiments performed by human workers. The basic idea behind the Life Science Assistant (LiSA) is to employ a mobile service robot to interconnect equipment. Flexible automated experiment cycles are obtained, while stations can be simultaneously used for other purposes. In addition, the robot helps employees prepare experiments, e.g. by collaboratively executing transportation tasks or filling microplates. Figure 2 presents typical objects the LiSA robot has to deal with in this scenario.



(a) (b)

Fig. 2. Typical objects used in a laboratory environment: microplate (a) and a drawer in lab equipment (b).

The following sequence illustrates a typical transportation task completed with the assistance of the LiSA. The user commands LiSA to take a sample from the preparation table and measure its fluorescence. The user additionally directs LiSA to place the sample in the drying chamber afterward.

1) The user gives LiSA the command in natural language.
2) LiSA approaches the table.
3) LiSA takes the microplate from the exchange area.
4) LiSA navigates to the fluorescence reader.
5) LiSA places the microplate in the drawer of the fluorescence reader.
6) The fluorescence is measured. (LiSA may complete other jobs at this point.)
7) LiSA removes the sample from the fluorescence reader.
8) LiSA navigates to the drying chamber.
9) LiSA places the sample in the transfer lid of the drying chamber.
10) LiSA notifies the user that the task has been completed.

This scenario has been simplified for purposes of illustration and presents just one possible use case. In reality, several interlocked tasks may be executed simultaneously. However, the model sequence highlights the different challenges faced.

IV. Project Objectives

Partially funded by the German Federal Ministry of Education and Research (BMBF) the LiSA project is constructing a demonstrator that completes the tasks described above. The specific objectives of the project are:

- Development of a mobile platform capable of navigating a laboratory with narrow corridors and doors. The platform has to meet high safety standards to receive official approval.
- Platform navigation in the dynamic environment of the laboratory. The robot has to detect nearby people and other objects early enough to avoid collisions and prevent injuries and damage.
- Development of a manipulator for handling relevant objects and interacting with human beings. The robot arm and gripper also have to meet high safety standards. Therefore, miscellaneous sensor systems are being designed to ensure as much safety as possible.

- Visual recognition and localization of objects and shelves. Stereo vision determines the position and spatial orientation of the microplates. Therefore, a stereoscopic camera system is employed. This system allows 2-D real-time position tracking and the computation of 3-D samples from the object surface to exactly guide the manipulation system.
- Multimodal human-machine interaction. If users are to accept it, commands given to the robot assistant have to be as intuitive as possible. LiSA is equipped with a touchscreen combined with a spoken dialog system. These two modalities can be used interchangeably and input in one modality can be augmented with input in the other.
- Integration of the aforementioned components in a working demonstrator.

The main priority of each of these objectives is safety, i.e. the robot may not harm any people or damage its environment. Even though safety is a prerequisite to official approval for the mass market, most other projects have disregarded this important aspect. Safety takes on even greater importance in the life sciences because the robot may deal with toxic or hazardous substances.

The hardware setup chosen consists of a mobile platform and a robotic arm and is described in this paper in section V. The safety requirements arising from the scenario are depicted in section VI. The following chapters deal with safe navigation in the tight laboratory environment (section VII), recognition of objects and humans in front of the robotic arm (section VIII) and the multimodal interaction with the robot (section IX).

V. Hardware Setup

A concept of a mobile robot assistant has been developed during the first steps of the LiSA project. It constists of a custom build scara robotic arm, mounted on a holonomic mobile platform.

The mobile platform is equipped with two independently steered wheels resting on inclined edges. To prevent the platform from buckling laterally, two additional castor wheels rest inside the remaining edges. One of these castor wheels is cushioned to ensure all wheels constantly remain in contact with the ground even when it is bumpy. This wheel configuration furnishes the mobile platform with advanced navigation capabilities, i.e. the platform is able to turn in place and move laterally. These are fundamental features ensuring the high maneuverability needed to navigate in tight environments such as in laboratories. The platform is able to travel at speeds up to 0.8 m/s. For navigation the platform is equipped with a gyroscope, wheel encoders on the driving wheels and six 2-D laser scanners. The gyroscope and wheel encoders track the platform's current orientation and movement. The laser scanners provide additional data for navigation and obstacle detection. For safety applications the laser scanners provide an alert area and a protection area. The safety system is completed by bumpers mounted all around the bottom edges of the mobile platform. If an obstacle violates the alert field of a laser scanner, the mobile platform slows down. Just as pressing one of the emergency stop buttons, activation of the protection area or of any other safety sensor element will result in an immediate stop. The mobile platform carries all required power supplies to ensure autonomous operation up to 6 hours. Navigation is executed autonomously. This claim results in extremely high safety requirements to protect men and environment from damage by the mobile platform.

The main task of the robotic arm is manipulating the environment, i.e. griping and transporting objects. As pictured in Figure 1 it is centrally mounted atop and towards the rear of the mobile platform. Thus, the arm is able to operate to the left or right of the mobile platform. The initial goals for robotic arm development included not only the desired functionality but also simple construction to easily integrate and evaluate sensor/actor elements for collision avoidance. Based on these requirements, a classical SCARA arm design was selected. The robotic arm consists of three joints with three vertical rotation axes and one linear axis at the front of the manipulator. The linear axis supports a 2-finger gripper. The manipulator is covered by a pressure-sensitive artificial skin for collision detection. The skin's design enables localizing the collision area. The chosen design gives the manipulator clearly defined directions of movement (horizontal for the joints, horizontal and vertical for the linear axis). Therefore, tactile sensor elements only have to cover specific areas. Torque measurement and contouring error control are integrated in the joints as additional electronic safety functions. As the final link in the safety chain, the manipulator is padded to prevent injuries in the case of a collision.

The robotic arm is equipped with two camera systems for camera-guided movement. A stereo camera system is installed near the linear axis, while a combined camera system (see section VIII) is mounted at the base of the robot arm as can be seen in Figure 1. The combined camera may be rotated independently from the robotic arm but should always be trained on the gripper.

VI. Safety

In all cases men and machines interact physically with each other it is obvious that strict safety precautions are needed. Despite several approaches to develop safety standards for robot assistants, standard procedures or solution catalogues for safety compliant design of robot assistants does not exist. A first approach to integrate men-machine interaction into international safety standards has been done within the EN ISO 10218. Basic claims concerning to EN ISO 10218-1 are:

- TCP (tool center point) speed reduced to 250 mm/s, supervised by security systems corresponding to Kat. 3 (ISO 13849-1)
- maximum acting force of 150 N and reduced power of 80 W both supervised by security systems corresponding to Kat. 3 (ISO 13849-1)
- survey of the TCP position, ensuring safe distance to interacting humans

- immediate stop if humans enter the robot's workspace (undercutting the safe distance)

Obviously these are just first hints for the design of men-machine interaction systems. A lot of work has to be done by the standardization authorities to create clear guidelines for the design of men-machine interaction systems and especially for autonomous robotic systems.

As long as explicit design rules do not exist, a risk analysis according to EN 1050 is the initial point to recognize potential hazards. Afterwards the system components may be designed within an iterative process to ensure conformity with EN ISO 13849-1. As described in [8], there are several approaches for safety compliant design of robotic assistance systems even under the actual safety rules for machines/robots.

A first iteration of LiSA's safety system is described in section V. In further iteration steps the safety concept has to be refined to reach the compliance with international safety regulations. Right now the reduction of forces and TCP speed is an integral component of the safety system.

VII. Localization and Obstacle Avoidance

The LiSA robot employs a new sensor configuration designed to improve safe navigation in tight environments. This sensor configuration combines 6 laser scanners to a robot centered 360° 3-D laser scanner that enables the robot to navigate with full 3-D obstacle avoidance.

Two laser scanners (SICK s300) are mounted on opposite corners of the robot. The scanners' 270° field of view generate a 360° field of permanent 2-D view even with overlapping regions (see green laser beams in figure 3). This combined 360° scanner serves two purposes: (1) in conjunction with odometry, it is used for localization in a prior map (and is therefore called "localization scanner" below); (2) it acts as the safety sensor necessary on the holonomic platform for constant avoidance of collisions with humans. It is insufficient for general obstacle avoidance, since obstacles may interfere with the robot in its complete bounding box.

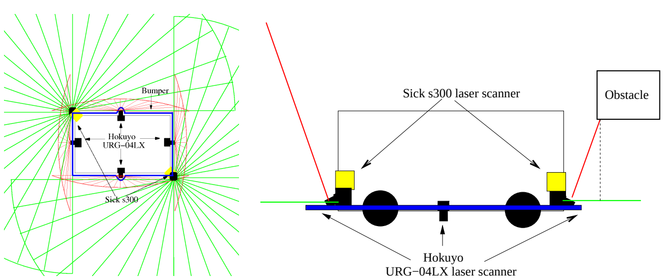
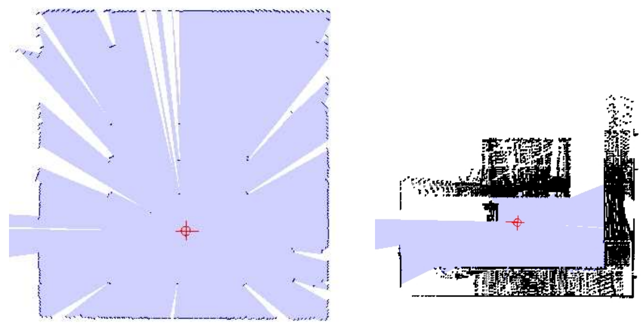


Fig. 3. The LiSA robot's laser sensor configuration: Two SICK s300 scanners (green laser beams) and four Hokuyo laser scanners (red laser beams).

To obtain 3-D obstacle avoidance, the setup is extended by four Hokuyo URG-04LX laser scanners each of which is mounted at the bottom of one side of the robot and angled upward (see red laser beams in figure 3). These sensors enable the robot to detect obstacles above the horizontal plane of the localization scanner. If an obstacle is detected in the respective data the 3-D laser data point (belonging to the obstacle) is projected to the floor plane and inserted into a local perception map. As the robot is moving it generates a detailed perception map of its immediate environment. The local perception map is combined with the localization map regarding the current robot position. This approach is illustrated in figure 4. Figure 4(a) shows the environment as it is observed with the localization scanner. Only the legs of tables and chairs are detected. The local perception map obtained with the Hokuyo scanners is depicted in figure 4(b). In this map the table tops are detected additionally.



(a) (b)

Fig. 4. Localization map generated with two horizontally mounted laser scanners (a) and improved obstacle avoidance map obtained with LiSA's sensor configuration (b).

The complete system has been tested in the robot simulation environment USARSim [11] with the simulation environment connected to the hardware abstraction layer of Player/Stage [12].

VIII. Computer Vision and Thermography

In this section we presents basic approaches to camera-guided movement of the robotic arm and its gripper as well as additional functionality to support the safety elements. In particular, the computer vision approaches to identify and recognize the exchange positions and the microplates are examined. Furthermore, the thermographic component for determining human interaction is described.

To reliably position the gripper vis-à-vis objects being picked up, two digital cameras sample are mounted near the linear axis of the robotic arm (see figure 1). These camera sample the immediate environment of the gripper. The cameras' color depth of 8 bits and resolution of 1032×778 pixels represent a compromise between computation time required for image processing and the accuracy of the result required. The lenses employed enable capturing an area of about 400×300 mm. By using subpixel interpolations, a resolution of ca. 9 pixels/mm^2 is produced, which is sufficient for determining the necessary positions.

The detection of the microplates at the exchange positions is based on a fast and adaptive segmentation approach. In a first step, a histogram is computed. As proposed by Rosin [13], the histogram value at the half between the minimum and the maximum is taken as the binarization threshold. The segmented result represents the area of the microplates and defines the required orientation of the robotic arm and its gripper. A black foam was found to optimally eliminate artifacts from reflections and uneven lighting. Furthermore, the exchange positions are labeled with coded markers (see figure 5(a)). This enables comparing the robot's actual position with the expected one and utilizing further algorithms to compensate for uncertainties from the global navigation.

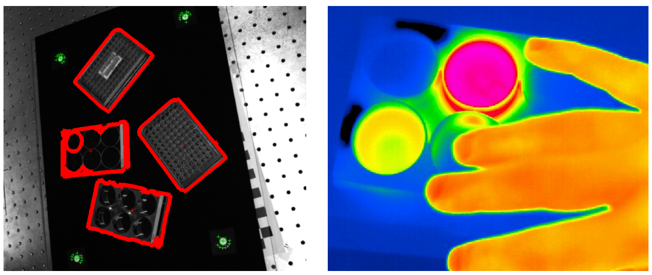


Fig. 5. Components of LiSAs optical system. Detection of microplates (a) and thermographic component for easily detecting human interaction (b).

The determination of exact 3-D position and orientation is based on a photogrammetric approach. Therefore, both digital cameras are used. Their positions and orientations are predetermined in a prior calibration step [14]. The triangulation principle serves as the basis for calculating the relative 3-D coordinates of objects visible to both cameras. Corresponding pixel pairs are identified by using statistical correlation between image segments on the epipolar lines [15]. The small base distance b of 150 mm necessitates aligning the camera's perspective to attain sufficiently high precision (< 0.5 mm) in the stereo-vision approach based on triangulation. When the robotic arm moves, the algorithms track the 2-D position of microplates on the one hand and take 3-D samples of the object's surface on the other hand. The resulting height data supports algorithms to detect plates on the top of one another.

To ensure the safety of the manipulation process a thermographic component is employed. This infrared component is part of a third combined camera device. As depicted in figure 1, this camera is mounted on a rotating stage and moves adaptively as the robotic arm moves. Basically, the combined camera device consists of two cameras, one for the infrared and one for the visible spectrum. The integrated cameras are calibrated to enable this system to merge visible and infrared images. The resulting four dimensional information (p_x, p_y, I, T) is utilized to detect human interaction in front of the robotic arm and its gripper (see figure 5(b)).

IX. Interaction through Speech

The interaction with the LiSA robot is multimodal, i.e. spoken and touchpad input are possible. The commercial dialog engine used for LiSA supports natural language dialogs and conversation in full sentences. For the LiSA project it is expanded for multimodal input. Experiences for this can be taken from the SmartWeb [16] and SmartKom [17], [18] projects. The dialog engine extracts all pieces of information from the spoken utterance and the touchpad input events. Orders and information requests can be placed via a spoken dialog with the robot, or via touchpad input. LiSA can have two independent users, each has a touchpad for graphical and a bluetooth headset for spoken input. The touchpad and the headset communicate with the robot via WLAN.

Both modalities, spoken and graphical interaction, are closely coupled, i.e. touchpad input influences the spoken dialog and vice versa. The system always replies on both channels simultaneously. The headset output which, for example, asks for the location of an object, will be combined with a laboratory map or a list of possible locations displayed on the touchpad. This is illustrated in the following dialog:

System:	What can I do for you? [display: status]
User:	Take the sample to the drying chamber in room 112.
System:	Where is the sample located? [display: map]
User:	At the pipetting station here. [touching a room on the map]
System:	Order will be executed. [display: list of orders]

The robot itself can send messages to inform the users about problems and error messages, or to notify them about completed orders, etc. Error messages will interrupt any ongoing dialog. After the problem has been fixed, the interrupted dialog can be continued. The described features generate a mixed-initiative, multimodal interaction between the laboratory assistants and Lisa. The intuitive interaction is a foundation for an efficient cooperation between human and robot in the laboratory.

X. Conclusion and Further Work

The LiSA project is concerned with the development of a robot assistant for laboratory automation that allows for safe interaction with human beings. In this paper we laid out the requirements and emphasized the importance of safety standards necessary for a service robot to operate safely in an environment shared with humans. The design of the mobile platform and the robotic arm incorporate these requirements in the various safety sensors such as the laser scanners, bumpers, thermographic components and artificial skin, which are designed for maximum safety. During further development the safety concept will be refined to reach the compliance with international safety standards.

The approaches to object recognition and multimodal interaction were also elucidated. Object recognition relies on stereo vision to determine the exact 3-D position of objects. This information is used to guide the robotic arm to its gripping position. Multimodal interaction incorporates spoken and touchpad input. These two modalities can be used interchangeably or even conjointly.

Further steps in LiSA project work will involve refining and implementing the concepts described here. All aspects of the development work will converge in the construction and testing of the final service robot by March 2009.

Acknowledgment

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