A Mobile Service Robot for Industrial Applications

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Abstract: This paper addresses the challenge of introducing mobile robots in industrial applications, where changes in the working environment and diversification of tasks require flexibility, adaptability and in some cases basic reasoning capabilities. Classical industrial robots hardly permit to meet these requirements, so a new concept of service robots facing challenging industrial production system needs is proposed. The realization of such an autonomous agent is illustrated and described in details, focusing on mobility, environmental perception and manipulation capabilities. The result is a mobile service robot able to face changeable conditions as well as unexpected situations and different kinds of manipulation tasks in industrial environments. In this paper an implementation dedicated to household appliances production is described, but the results achieved can be easily extended to many industrial sectors, goods and electromechanical components where high levels of flexibility and autonomy are needed.

1 INTRODUCTION

At the state of art, robot applications are usually divided into two main categories: industrial robotics and service robotics (Bekey and Yuh, 2008). In the past these two fields were widely unrelated and disconnected so that they were considered as fully independent from each other. Industrial robots mainly operate in highly structured environments, and they are not able to adapt to frequent changes and variations in the environment. On the other hand, nowadays, systems able to cope with flexible and complex tasks in changeable environments, as well as with uncertainties and unpredictable modifications of the working area can be widely found in the field of service robotics: e.g. Care-O-bot (Reiser et al., 2009), PR2 (Bohren et al., 2011) and many more.

Although recent evolution in sensors technology and modern developments in control algorithms (Wang and Li, 2009) have brought to an extensive variety of service robots, very few of them seem to deal with the support of industrial processes (Hamner et al., 2010). Therefore, all the progress achieved in the service robotics domain has not yet fully exploited in the industrial field. For example, a closer interaction between robots and humans inside the production environment is still an open issue but it could be solved using techniques fully exploited in service robotics applications, thus permitting the sharing of the same working area between robots and humans.

Industries need robotic systems which are flexible, modular and easily customizable to the requirements of different production processes. A mobile robot with manipulation capabilities represents a valid solution for achieving the level of flexibility required by modern industrial processes (Kroll and Soldan, 2010). Most of the possible alternative solutions, like gantry mechanisms or robots running on conveyor systems need a highly-structured environment, and they could turn out to be completely useless in the case of environment changes.

Nowadays mobile robots applied in industrial applications mainly belong to the group of AGVs (Automated Guided Vehicles) with their main purpose to transport objects from one location to another. They mostly follow pre-programmed paths and are able to react to their environment only in a limited way: usually the robot stops in case its

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sensors perceive an obstacle in its path. First systems of AGVs with attached robotic arms have been set up in Japan (Hibi, 2003). While robotic arms deliver high flexibility, until now there are still unsolved problems considering energy consumption, weight and safety. In this way, AGVs equipped with robotic arms are not wide spread especially in Europe and they are applied only to very specific domain like offshore platforms (Bengel et al., 2009).

Another major challenge in using a mobile robot in an industrial environment is to ensure collision-free operations in order not to endanger humans sharing the work space and not to crash against unexpected obstacles in the working area. Safe human-robot cooperation is a mandatory topic that has to be considered and assured for this kind of applications. Mobile robots like AGVs are able to move safely in their environment. This is realised by various sensors (mainly bumpers, plastic brackets and laser scanners) ensuring that no collision occurs (Ikuta and Nokata, 1999). The safety of robot arms, however, is mostly still ensured by separating their work areas from humans with fences. Safe human robot interaction according to ISO 10218 requires special safety controllers and additional devices such as safety sensors or dead man switches. So far, no industrially used implementations to detect and avoid collisions of robot arms have established in either unknown or changing environments without using fences (Oberer and Schraft, 2007).

This paper is going to present a mobile system achieving a degree of autonomy and flexibility typically found on robots belonging to the service robotic field but specifically conceived for working in industrial scenarios.

2 SYSTEM OVERVIEW

The developed system is a mobile service robot with manipulation and environmental perception capabilities, conceived to work in industrial environments with a high degree of autonomy and flexibility (Figure 1). The robot is able to:

- Move safely and autonomously in an industrial environment following predefined paths, avoiding obstacles and collisions, detecting targets and reaching objects;
- Reconstruct a 3D model of the working environment and recognize relevant features;
- Interact with objects in the surrounding environment performing operations like grasping, pushing buttons, turning knobs and opening / closing doors;

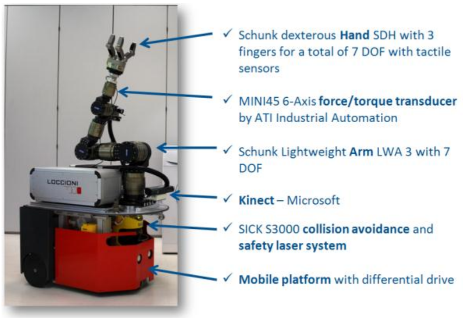

Figure 1: Overview of the developed mobile service robot.

- Place advanced sensors (digital cameras, distance sensors, tactile sensors, temperature sensors, pressure & sound sensors, etc.) in order to gather new information;
- Acquire, analyse and collect data.

3 NAVIGATION CONTROL

The key aspect of an autonomous mobile robot is represented by its ability to freely move in the working area, localizing in the environment, checking for possible obstacles along the planned path and avoiding collisions during motion. Figure 2 describes the overall architecture of the implemented navigation control system. The most important modules are described in the following subsections.

3.1 Obstacle Detection

Collisions avoidance during robot motion is based on SICK Laser Scanner and Microsoft Kinect sensors. Kinect 3D sensors, covering the floor area close to the robot, are used to sense obstacles which are not visible with the laser scanner (e.g. a table plate). The raw data acquired from these sensors is filtered so that only relevant obstacles in the driving direction are taken into account for the collision model. The raw point cloud is transformed into the

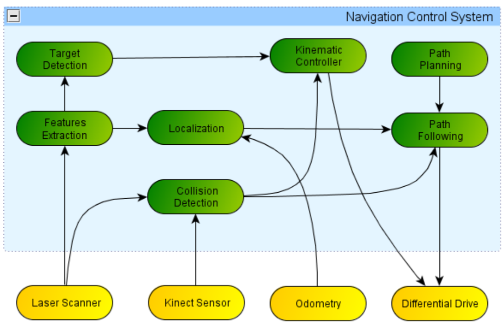

Figure 2: Navigation control system.

robot base coordinate system and further filtered to remove points that are in the ground and beside or above the robot. With the help of the odometry information which specifies driving direction and speed, the minimum stopping distance for the robot is calculated.

The safety distances can be adapted according to the environment the robot is working in and depend on the speed of the robot. If an obstacle is detected, the robot will be stopped in order to plan a new path for avoiding the object.

3.2 Environmental Feature Extraction

By filtering and processing data acquired from the laser scanner mounted on the robot, the system is able to detect spatial primitives in the working environment (corners, straight lines and reflective landmarks). The line extraction algorithm implemented is similar to the one described in Armesto and Tornero (2006) and it is based on two steps: *split* and *merge*. During the splitting step if the distance between two consecutive points acquired by the laser scanner is below a certain threshold the points will be considered as members of the same cluster, otherwise they belong to different ones. Inside the same cluster the Least Mean Square (LMS) algorithm is used to find the segment that approximates the position of the points. During the merging step if consecutive segments are close and aligned, they are approximated with another segment including both. The merging step is repeated until there are no more segments to merge. In Figure 3 the result of applying the line extraction algorithm to data acquired by the laser scanner is depicted.

3.3 Robot Localization

Localization presumes that the mobile system is able to recognize environmental features like walls, corners, columns. In the implemented algorithm, the capability of the laser scanner to detect reflecting markers is exploited. In order to avoid detection errors, consecutive reflective points are considered markers only if:

$$N = \frac{L_{marker}}{\rho R_{laser}}$$

where N is the number of consecutive reflective points, L_{marker} is the diameter of the marker, R_{laser} is the laser scanner resolution and ρ is the distance between the laser and the reflective surface. Once markers are recognized by the features extraction algorithm, they are added to the environmental map

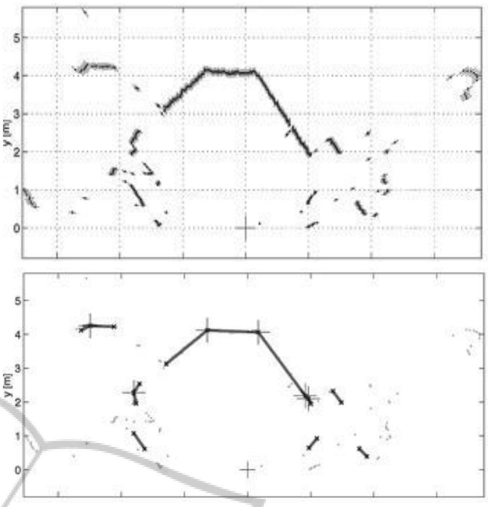

Figure 3: Data processing for lines extraction (upper: raw data, lower: processed data).

and then used in the localization process. The localization algorithm is based on a standard implementation of the Kalman Filter (Welch and Bishop, 2006), and it is composed of the two classical steps:

1. *Prediction*: the system forecasts the increase of the position error due to the inaccuracy of the encoders. The result of this step is the position of the robot plus an uncertainty level.
2. *Correction*: Kalman Filter is used to correct and reduce the position uncertainty using the position of the markers that have been detected.

4 MANIPULATION CONTROL SYSTEM

The following section will focus on the manipulator control system that makes the robot able to safely operate and interact with objects in the working environment.

4.1 3D Modelling for Arm Collision Detection

Detecting obstacles in the proximity of the robot and considering them in the movement planning phase allow the robot to operate its arm also in narrow environments. When the robot needs to move its arm, a collision-free path to reach the goal position is planned. All the movements of the arm have to be self collision free, which means that the arm should not collide with any other part of the robot. For this reason, a 3D model for the arm and the mobile base is used for collision checking: collisions between single joints composing the arm as well as between the arm and the mobile base (and with other robot components) are checked. This step is based on the internal joint sensors of the arm, so the robot knows about its own current configuration and its dimensions. Another important aspect is to check collisions against the environment. Industrial working environments, where the robot could be used, are not static, so the robot has to deal with dynamic obstacles. To supervise the arm two PMD CamBoard are used; one is directly mounted on the arm, while the other on the mobile base. To not detect the robot parts themselves as obstacles a robot self-filter is setup removing the robot parts from the 3D point cloud.

4.2 Manipulation

For the proper execution of an interaction task, the target coordinates of the object to be manipulated (that are expressed with reference to the sensors coordinate system) are transformed into the Tool Center Point (TCP) reference system of the arm. Then the arm moves in front of the target using inverse kinematics, arm planning and collision checking against the above mentioned 3D robot and environment model. The manipulation system is set in order to pre calculate all arm movements taking into account the 3D environment model. Only if all movements and target positions can be reached, the execution is started. In that way it is assured that the arm does not need to be stopped in the middle of a task because of reachability issues. Nevertheless the arm will be stopped due to safety issues, e.g. collision sensed with the tactile or FT sensors.

As a manipulation task requires physical contact between the end-effector and the object, in the "contact phase" of the task it is not possible to use the planning with collision checking approach described in the previous paragraph. Touching the target with the end-effector of the arm would be considered of course as a collision. Therefore the arm moves just in front of the target object and then the manipulation mode changes in order to move very slowly to a pose which is already inside the target. The arm will stop as soon as the contact is detected by tactile or force-torque sensors. This approach avoids problems due to inaccuracy in the depth information acquired by the 3D sensor and prevents damages to the target objects and the robot itself. Furthermore using the above strategy the robot is able to safely execute the desired operation even within a changing environment.

5 APPLICATION SCENARIO AND EXPERIMENTAL RESULTS

The capabilities of the proposed robot have been fully tested and validated in a specific industrial application scenario: the reliability control in life-test laboratories of household appliances.

5.1 Scenario Description

Today in washing machine (WM) life-test laboratories, machines functional performances are usually recorded, such as the quantity of water and energy consumed. The level of automation of such tests is relatively low; in most cases, human operators are in charge of loading the machines with cloths, starting the washing cycle and periodically controlling that no failure occurs. Once a failure occurs, the number of washing cycles until failure is recorded and fed as input to the following reliability analysis (together with the type of failure).

With respect to this context, the developed mobile robot can be equipped with additional measurement sensors (in particular a laser vibrometer, a microphone and a high resolution 2D camera) in order to properly inspect the working behaviour of a washing machine. In the described scenario, such a "diagnostic service robot" represents an excellent solution because it satisfies the needs of standards and repeatability of the quality controls and guarantees flexibility according to the product under diagnosis and the environment where the test is executed (Concettoni et al., 2011).

5.2 Products Detection and Approach

In order to autonomously achieve its diagnostic task, the robot needs to recognize washing machines in the environment and reach the machine to test (Raffaeli et al., 2012).

The feature extraction algorithm described in Section 3.2 is used to detect both front and side faces of the washing machine. Knowing the WM geometrical data (depth and thickness), the position of the center of the potential washing machine is calculated and this value is compared with its expected position (the nominal position of the machine is known from the map of the laboratory). Only if these values match (with an appropriate error tolerance) the object detected will be considered as the washing machine to test, and the final target position of the robot (as well as its orientation) is calculated (Figure 4). The results obtained applying the “detection and approach” algorithm are shown in the first sector of Table 1.

5.3 Products Visual Inspection

As the diagnostic procedure depends on the actual working condition of the product to test, based on data collected by the 2D camera the system is able to correctly recognize the WM functional status (off, washing, etc.). The acquired image is first filtered and processed, so that effects of reflections and light variations can be minimized. First, a median filter is applied to the image, as to increase edges contrast. Then a Laplacian of Gaussian (LoG) smoothing technique is used in order to further highlight edges. Next, the filtered image is processed in order to detect the washing machine edges (top, right and left). At this point, the washing machine features defined in the front panel map (known by the robot as the panel maps of all washing machine models to inspect are stored in the reliability laboratory database) are relocated in the new reference system of the acquired image. Machine vision algorithms are used to check whether the LEDs are ON or OFF, and to get the characters visualized in the display (if present in the front panel). Figure 5 shows an example of visual inspection of a particular model of washing machine. The results obtained applying the visual inspection algorithms are shown in the second sector of Table 1.

5.4 Products Interaction

In order to acquire useful diagnostic data from the washing machine under test, the robot could need to interact with the front panel of the appliance. In this particular application scenario, the manipulation capabilities of the robot allow to push buttons, turning knobs and opening doors.

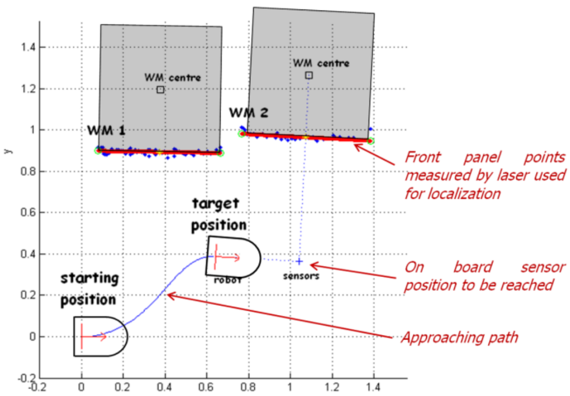

Figure 4: Robot motion planning for a WM approach.

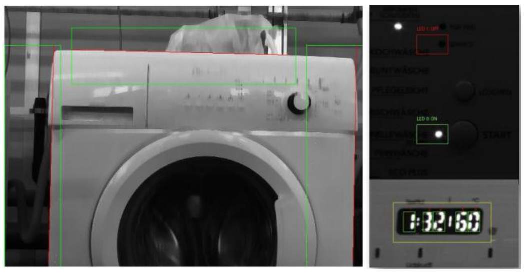

Figure 5: WM edge recognition (left) and panel inspection (right).

Whenever a manipulation task is required, the robot detects with the laser scanner the corner of the washing machine (using the line extraction algorithm described in Section 3.2 and Section 5.2) and then, from the map of the front panel (stored in the reliability laboratory database) the position of the feature is relocated in the arm reference system. This algorithm permits to achieve the required accuracy in the position estimate of the desired feature. Moreover, every movement of the arm (except the very last part of the interaction with the washing machine front panel) is monitored by the “collisions checking” module, as to prevent collisions with obstacles in the environment. The final part of Table 1 summarizes the results obtained in the execution of the interaction tasks.

6 CONCLUSIONS AND FUTURE WORK

In this paper the development of a service robot for industrial applications has been presented, focusing on the main aspects related with autonomous systems development: navigation, perception and physical interaction with the real world.

Table 1: Experimental results for WM detection and approach, visual inspection and interaction tasks.

	WM#1	WM#2	WM#3
WM DETECTION AND APPROACH			
Detection failure rate	<1 %	1 %	1 %
Position detection error	0.02 m	0.03 m	0.03 m
Approach position error	0.03 m	0.05 m	0.04 m
VISUAL INSPECTION FAILURE RATES			
Edge detection	4 %	3 %	4 %
LED ON detection	1 %	2 %	2 %
LED OFF detection	1 %	2 %	2 %
Display char detection	5 %	n. d.	n. d.
INTERACTION TASKS FAILURE RATES			
Push button	3 %	2 %	2 %
Turn knob	n. d.	4 %	5 %
Open door	n. d.	2 %	n. d.

The main novelty of the proposed solution is a system that can guarantee high flexibility and effectiveness own to its mobile nature. A real application scenario was defined in order to fully validate and deeply test the system, and the results show its capabilities as well as its reliability.

Next activities aim at testing innovative approaches related to perception of the environment, in order to improve the navigation and interaction capabilities of the system. Future works will include the implementation of Particle Filtering techniques and fusion of multimodal sensor data (LRF data, 3D sensors data and 2D camera images). Issues concerning human-robot interaction and safety will be improved and refined. Robot manipulation capabilities will be also increased, making the system able to perform additional tasks.

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