Implementation of a Capacitive Proximity Sensor System for a Fully Maneuverable Modular Mobile Robot to Evade Humans

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Abstract—This paper describes an advanced approach for a dynamic collision prevention system for robots dedicated to collaborative applications in a shared human robot work environment. We developed a firmware that incorporates proximity sensor information along with a kinematic algorithm to achieve sensitive robotics for a modular mobile robot platform. The utilized sensor technology is based on capacitive sensing, capable to reliably detect humans in the vicinity of the robot platform. The kinematic algorithm is flexible in its design as it is scalable to an unlimited number of wheels and takes into account different geometric architectures such as standard and omni-directional wheels. The dynamic collision avoidance of approaching humans has been successfully demonstrated in a variety of experimental test scenarios demonstrating the capabilities of a sensitive mobile robot.

I. INTRODUCTION

A. Motivation

The number of industrial robots in production facilities is rising steadily. The demand from the industry to have a shared work environment, where humans and robots can work together safely has increased tremendously in the last years and will become an integral part of daily work life. Further, the shortening of a product’s life cycle generates the need of flexible production lines, where a sensitive and modular mobile robot platform fulfill logistics. This implies that a modular mobile robot platforms has to operate safely along with humans in a shared work environment throughout the entire time. A reliable perception system is essential to realize such a platform. The combination of kinematics of a modular mobile robot platform tightly coupled with collision avoidance technology, i.e. proximity perception sensors, are considered in this paper to safely operate a modular mobile robot platform in a shared human robot space.

B. Background

A great variety of proximity sensing technologies are available at the market such as capacitive, optical, etc. today and used in robotics. Each technology has its capabilities and comes along with benefits and limitations. Optical systems [1] have some limitation with respect to strong varying light conditions and reflections. Compared to that capacitive sensors [2] show strong non-linearities depending on the material properties and coupling to ground which can be stabilized by incorporating a proper signal processing. Thus, capacitive sensors are well known in robotics. In [3], a highly reactive collision avoidance system based on capacitive proximity sensors was evaluated. In [4] capacitive based proximity sensors were utilized on a serial manipulator to detect approaching objects in one dimension combined with a virtual compliance control of a redundant manipulator to avoid approaching objects. Further enhancements in [5] presented a contactless control of a serial manipulator based on capacitive tomographic sensors. Both works have shown that the perception system is tightly coupled to the kinematics of the robot to make them collaborative and to gain advantage of the robot’s redundancy. The sensing range and characteristics of the capacitive sensors is strongly related to the geometry of the sensor front end. Investigations in [6] where done to evaluate different geometrical shapes of the sensor front.

C. Contribution

In this paper we present a fully maneuverable modular mobile robot system with integrated capacitive proximity sensors including dynamic collision prevention with humans.
The developed advanced kinematic algorithm provides independability in terms of hardware realizations of the wheels, i.e. the modular robot platform can either consist of steered standard wheels or omni directional wheels. Furthermore, the modules of the robot can be arranged according to the needs of the application, e.g., a logistics task.

II. SYSTEM DESCRIPTION

A. Modular Wheeled Robot

The utilized modular mobile robot platform (referred to as Wabenroboter) consists of several hexagonal shaped submodules (referred to as hive module), each capable to be equipped with different hardware, e.g., serial manipulator. In this work two hive modules with a steered standard wheel, one hive module with a castor wheel and one hive module containing the Central Processing Unit (CPU) (Intel NUC) are utilized. The hive modules have a side length of \( w = 123 \text{ mm} \) and the main body consists of two plates stacked on top of each other, each \( h_p = 90 \text{ mm} \) in height. The wheel extends downwards for \( h_w = 123 \text{ mm} \), which results in a total height of around \( h = 300 \text{ mm} \). The robot geometry, as in how the hives are fixed together does not matter, for testing purposes we used the layout as shown in Fig. 1.

B. Software Architecture

The firmware consists of three main parts: The sensor signal processing module (Sensor Interface) including position estimation of an approaching human to generate a directional vector in which the robot should evade. The kinematics module (Kinematic algorithm), which determines the orientation and velocities for each wheel instantaneously. It passes the data to the module which communicates with the motor controllers (Motor Controller Interface). The overall software architecture is shown in detail in Fig. 2.

As a basis for the firmware of the robot the framework ROS (Robot Operating System) [7] is being utilized. Each part of the robots software is implemented as its own ROS package. The individual packages communicate through the ROS Publisher/Subscriber system using custom messages. To avoid communication time lags between the kinematics algorithm and the motor controller the kinematics algorithm is installed native package on the linux host. An interface class in the motor controller code enables the communication between them.

III. SENSOR TECHNOLOGY

The sensor technology in use is a capacitive proximity sensor. The measurement principle is based on the interaction of an electric field with an object approaching the sensor front end of the capacitive proximity sensor. The distortion of the electric field is caused by an object depending on its relative permittivity \( \varepsilon_r \) which can be measured. For proximity sensing usually the so called single-ended measurement mode is commonly utilized as illustrated in Fig. 3. In this measurement mode the capacitance between the transmitter electrode and the distant ground is determined. Therefore, an excitation signal with the frequency of \( f_{ex} = 250 \text{ kHz} \) is sent to each electrode in succession and the current of the displacement current is measured.

The sensor node’s Printed Circuit Board (PCB) with the evaluation electronics is being supplied with 5 V and consists of an ultra low power wireless System on a Chip (SoC) and a 16-bit Capacitance to Digital Converter (CDC). The sensor front-end is made of a conductive copper film connected to the PCB. The measurement data is transmitted wireless with a frequency of \( f_T = 2.4 \text{ GHz} \) to a receiver dongle connected to the Intel NUC of the modular mobile robot platform.

The measurement characteristics of the sensor are highly dependent on the shape and size of the connected electrode’s of the sensor front end which can be individually designed according to the needs of the application. In this work the size is restricted by the geometry of the hive module’s side walls.

The size of the surface of the electrode, is strongly related to the maximum sensing range objects can be detected. However, increasing the size of the surface also results in the sensor being more prone to detect disturbances and noise. In Fig. 4 the shape of the electrodes used in this work are shown.

IV. KINEMATICS

A. Kinematic System

The Wabenroboter is designed in a modular way, therefore the position and the number of wheels can change (while it is not operating). The mobile platform supports steerable standard wheels, as well as omnidirectional wheels and is configured in a way that the degree of maneuverability \( \delta_M \) equals three.

The Wabenroboter is operating in a two-dimensional space so the position can be distinctly defined in \( \xi \) which holds
the direction in $x$ and $y$ as well as the orientation angle $\theta$. To describe the motion of the robot the values of $\xi$ must be differentiated over the time to describe the velocity of the robot. Information on how the robot should move is received by a given trajectory which contains the velocity of the platform over time. Hence, the kinematics input is given as velocity vector $\mathbf{\dot{\xi}}$.

$$\mathbf{\dot{\xi}} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{\theta} \end{bmatrix}^T$$

### B. Kinematical computations

As well known from literature the kinematics of mobile robots can be modeled by using equations in the form of rolling and sliding constraints. For this work the Wabenroboter is equipped only with steerable standard wheels. These wheels are equipped with an additional vertical axis of rotation in comparison to fixed standard wheels which enables it to change $\beta$ with respect to time. Hence $\beta$ becomes $\beta(t)$ in the kinematic constraint equations. The vertical axis of rotation passes through the center of the wheel and the ground contact point. The rolling and sliding constraints are given for a standard steered wheel as [8]:

$$[\sin(\alpha + \beta(t)) - \cos(\alpha + \beta(t))] \dot{\xi}_R - r \dot{\phi} = 0$$

$$[\cos(\alpha + \beta(t)) \sin(\alpha + \beta(t)) - l \sin(\beta(t))] \dot{\xi}_R = 0$$

In the equations above, $\alpha$, $l$ and $r$ are geometrical values as can be seen in Fig. 5 and $\dot{\phi}$ denotes the wheel velocity.

Much more intuitive is the geometrical view on kinematics of mobile robots. By calculating the distance of each wheel to the instantaneous center of rotation (ICR) and fulfilling the sliding constraint of the steerable standard wheel, the steering angle of each wheel is calculated. When omnidirectional wheels are used, the mobility $\delta_m$ of the robot equals three and the robot is therefore able to manipulate its position (in two-dimensional space) in every direction as well as turning around an arbitrary point. By using the rolling constraint of the equipped wheel type the rotational speed of each wheel is calculated while taking its position into account. Moreover, using the geometrical consideration the steering angle of a standard wheel $\beta$ can be calculated by

$$\beta = \arcsin \left( \frac{R \text{ ICR} \sin(\alpha_1)}{\sqrt{l^2 + R \text{ ICR}^2 - 2lR \text{ ICR} \cos(\alpha_1)}} \right), \quad (2)$$

where $R \text{ ICR}$ denotes the distance between the robots’ center $R$ and the ICR.

### C. Operation

During operation (e.g., following a path) the robot has to respond to sensor input and interrupt its current task if necessary. If only omnidirectional wheels are in use, the robot can instantaneously correct its velocity vector (except of dynamical influences) and therefore react to sensor input immediately. The wheels of a mobile platform with steerable wheels must be turned correctly to allow a preferred motion. This is the reason why such drives are called pseudo-omnidirectional.

### V. EXPERIMENTAL SETUP AND RESULTS

Experimental studies were done on both the robot system and the capacitive sensors. In a further step, the two systems were linked and tested together.

#### A. Sensor Evaluation

The characterization of the capacitive proximity sensor is performed on a linear axle for a well coupled object (similar to a human) as shown in Fig. 6. An angled profile beam is fixed on the slide of the linear axis and used to fix the electrode to avoid interferences caused by the linear axis itself. A grounded metal plate serves as the measured object. The electrode’s and metal plate’s surfaces are parallel during the entire test.
In Fig. 7 the measurement curve obtained from the test bench where an object approached the sensor front end is shown. The object is moved precisely in front of the sensor plane along $x = 0 - 200$ mm. The maximum achieved sensing range in this setup is $d_{max} = 60$ mm.

B. Simulation

The mobile robot platform was modeled in a simulation environment for rapid and extensive testing of the software framework. This means that even without real hardware, realistic scenarios like in the laboratory can be carried out. This was achieved by the simulation software Gazebo, which can be connected via the ROS framework, see Fig. 8.

The simulation is used during firmware development to verify the correctness of the code and visually demonstrate the entire system without using the robot. In addition to the modular mobile robot platform, the capacitive proximity sensor is also integrated into the simulation environment in order to evaluate the dynamic collision avoidance in the simulation before it is tested on the real mobile robot platform.

C. System Tests

In the experimental test setup (see Fig. 9) the modular mobile robot platform equipped with the capacitive proximity sensors drives on a predefined trajectory (sine curve) while a human approaches the robot from one side. As soon as the capacitive proximity sensor detects a human closer than $d < d_{max}$ the direction of the movement of the robot platform is changed immediately to dynamically react to the approaching human. Therefore, a contact between the human and the robot can be avoided. The modular mobile robot platform discontinues its primary task (moving on the predefined trajectory) if a human in the close surrounding of the robot is detected by the capacitive proximity sensor. If no person or object is recognized in a subsequent step, the main task is continued.

VI. CONCLUSIONS

In this work, a flexible firmware with capacitive proximity sensor information was developed to achieve dynamic collision avoidance for a mobile robot platform. The kinematic algorithm was developed to support various mechanical wheels and to increase the flexibility and modularity of the mobile robot platform. In addition, the integration of a capacitive proximity sensor on the modular mobile robot platform enables dynamic reaction and collision avoidance of the robot if a person approaches the robot. This enables the modular mobile robot platform to be used in a common human-robot environment. In the future a variety of electrode geometries will be evaluated to improve the sensing range of the capacitive proximity sensors.
ACKNOWLEDGMENT

The authors would like to thank Hubert Zangl, head of the Smart System Technology Institute, Alpen-Adria-Universität Klagenfurt, supporting the work, providing the sensor hardware platform. This work was mainly funded by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) within the framework of the sponsorship agreement formed for 2015-2018 under the project RedRobCo.

REFERENCES


