Robot Position Estimation on a RFID-Tagged Smart Floor

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Summary. We describe a navigation and position estimation system for mobile service robots which is based on RFID technology. This system avoids deficiencies of existing solutions and offers high flexibility and accuracy at moderate cost. The core idea of the system is to structure the work space by means of a *Smart Floor* in a manner which enables and supports reliable navigation and positioning with absolute accuracy over large distances. The "intelligence" of the floor is in a dense, area-wide network of thousands of RFID transponder, which are mounted underneath the regular floor covering and quasi serve as radio beacons. The system has been presented at CeBIT 2006 in Hannover by invitation of the German Ministry of Education and Research. InMach Intelligente Maschinen has further received the Walter Reis Innovation Award for Service Robotics for this innovative solution. It is important to note that although the primary focus of the work described in this paper is on the guidance of service robots in large-scale indoor environments, the Smart Floor described below provides the infrastructure for all kinds of location-based services which might be of relevance in a large facility. The economic value of these services may even exceed the economic value of automated cleaning.

1 Introduction

In this paper we describe a navigation and position estimation system for mobile service robots which is based on RFID technology. The design of this system avoids deficiencies of existing solutions and offers high flexibility and accuracy at moderate cost. The core idea of this system is, like for vehicles guided by wires or magnetic beacons buried in the floor, to structure the work space in a manner which enables and supports reliable navigation and positioning with absolute accuracy over large distances.

Structuring of the work space, however, does not involve the application of any visible markers or wires. Instead the workspace is equipped with a so-called smart floor – a key component of our approach – which neither in its basic physical consistency nor in its optical appearance differs much from a regular floor covering. The "intelligence" of the floor is in a dense, area-wide network of thousands of RFID transponder, which are mounted underneath the regular floor covering and quasi serve as radio beacons. A commercial version of such a smart floor has been developed by the German company Vorwerk Teppichwerke, which is a partner of InMach Intelligent Maschinen GmbH.

The second key component in our approach is the actual RFID based vehicle navigation system. While the vehicle is in motion, this navigation system senses the identifiers of RFID transponders in its proximity and computes an estimate of the absolute position and orientation of the vehicle and uses these data to guide the vehicles locomotion along a planned path.

Through their synergy these two key components *smart floor* and *RFID based navigation* provide a low-cost, flexible guidance system with absolute position accuracy for mobile service robots and AGVs. This solution has the potential not only to re-animate but also to boost the market for mobile robots for professional services which has ben almost disappearing in the past years.

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It is important to note that although the primary focus of the work described in this paper is on the guidance of service robots in large-scale indoor environments, the Smart Floor described below provides the infrastructure for all kinds of location-based services which might be of relevance in a large facility. The economic value of these services may exceed the economic value of automated cleaning by far.

2 State of the Art

The RFID based navigation system described here is not so much the result of a basic research activity or a prove of concept. It is an industrial prototype which is currently under field testing and which is supposed to reach series-production readiness by the end of 2007. It will be used in two professional applications first: in an *automatically guided transportation vehicle* (AGV) for hospital logistics and in a robot for professional cleaning. This short review of related work will therefore focus on professional guidance and navigation systems for mobile (service) robots and only briefly discuss basic research on RFID based navigation and smart floors. The state of the art in professional navigation systems will be shown in a few selected, highly representative systems.

2.1 State of the art in commercial mobile service robot guidance

Using mobile robots for professional services for example in the area of facility management is not a very original idea. Since the beginning of the nineties several attempts have been undertaken, to automatize burdensome, dirty, low-qualified tasks by means of mobile service robots. The following systems are representative for the state of the art in this field.

Helpmate was the first mobile service robot, which was specifically designed for logistic and transportation tasks in hospitals (1995). HelpMate had a rather extensive sensor configuration, which included amongst others a laser range finder, a set of sonar sensors, and a gyroscope. It used a floor plan and permanently installed markers for navigation. Helpmate was preferably used for transportation of food, medication, and laundry. In spite of the public and media interest, the commercial use of HelpMate has not become a success story. In total only 150 units were manufactured and installed [1]. Helpmate cost approximately US$ 110.000 per unit. Typically the system were not sold but leased for an hourly rate of US$

4 to 6. The yearly lease was US$ 110.000. It is not completely unlikely that the low number of installed systems is related to the rather high initial cost and the insufficient price-performance ratio.

A representative of the more recent developments in the area of service robots for professional cleaning is the robotic floor scrubber ST82 R Variotech of Hefter Cleantech, Germany. Its navigation system SINAS (Siemens Navigation System) included two laser range finder, an array of sonar sensors, a gyroscope and an odometry system. Using its sensors the system was capable of generating a map of its work space. ST82 R Variotech was distributed for approximately 50.000 Euro. Amongst others it was installed in a Dutch supermarket chain. One unit which was installed at the airport of Manchester, UK, was give to the Queen Elizabeth II Hospital in Welwyn Garden City, Hertfordshire in 2001. The manufacturing and sale of ST82 R Variotech has been discontinued [2].

2.2 Recent developments in the area of AGVs

For many years automatic guidance of vehicles by induction wires or magnetic beacons or optical markers were state of the art ([3, 5, 4]). Not until recently a sensor, which has significantly influenced and fostered basic research in mobile robotics, namely the SICK PLS and LMS sensor, has also expanded into the development of automatically guided vehicles (AGVs). A representative development is the system Transcar LTC-2 by Swisslog Telelift GmbH ([4]). Transcar LTC-2 uses two laser range finder (one in the front and one in the rear area) to sense and measure the environment. To estimate the position of the vehicle the perceived range images are compared and aligned with a give floor plan. One would expect that the system by using laser range finders has become significantly more flexible than traditional, wire-guided systems. This flexibility has its limits, however. For reliable position estimation and navigation a complete metric model (map) of the environment is required. In a second topological map way points for navigation are defined. The approach quasi implements a virtual automatic guidance. Cost for pre-structuring the work space can be avoided this way. However every change of the environment for consistency reasons requires an update of the metric map of the work space. Such an update may require a significant effort and cause significant cost. Automatically mapping the workspace, which has its own deficiencies, is not foreseen in this approach. Navigation in an unknown environment seems to be impossible.

2.3 RFID navigation and smart floors in basic research

There is not much basic research in RFID navigation and smart floor. The literature is accordingly sparse. Based on the patent situation it seems that industry has discovered this topic before the academic community. There is actually an significant number of patents or patent applications out there which address similar or almost identical problems: given we can distribute a sufficient number of RFID transponders over the workspace, how can a robot use such an infrastructure and the information encoded in the transponders to estimate its position and execute its mission. The approaches described in [10, 9, 6, 7, 8] address the same problem and provide very similar solutions. Typically the position estimation is solved by aligning and/or fitting the observations of one or more tags and their approximate position sensed by odometry to an established frame with known tag positions.

A frequently cited academic publication is the work by Hähnel et al. [11]. They generate maps of RFID tags with mobile robots and compute a posterior about the position of a tag after the trajectory and the map has been generated with a highly accurate FastSLAM algorithm for laser range scans. A concept of a Smart Floor equipped with RFID transponders was presented in [12]. This smart floor is primarily used for identifying and tracking people.

3 RFID Navigation on Smart Floor

The above described systems are representative for the state of the art in the area of commercial mobile service robots and automatically guided vehicles and their guidance systems. It is noticeable that even the "free navigating" systems lack a sufficient flexibility, which would allow a customer to deploy the vehicles in an partially unknown environment without costly system adaptations or modifications of the environment.

A feature, which is shared by the systems described in the previous section, is the significant cost for the navigation and guidance systems. These guidance systems use at least one, often several expensive laser range finder. The price for this component by itself (ca. 3500 Euro per sensor) exclude, that the vehicles can be brought to the market for less than 20.000 Euros. For many service robot applications, amongst them professional cleaning this is definite knock out criterion. All cleaning robot developments for professional cleaning in the past – approximately 15 in number – have died because of their cost regardless of the tremendous economic potential of automation of cleaning.

The innovative approach presented in the section below is a navigation system which avoids the deficiencies (lack of flexibility, hight cost) identified above. The core idea of this approach is to pre-structure the work space like in earlier approaches using induction loops and magnetic beacons in order to enable reliable navigation and absolute positioning with high accuracy over long distances. Our navigation system operates on a so called smart floor, a dense, area-wide network of thousands of RFID transponder, which are mounted underneath the regular floor covering and quasi serve as radio beacons.

The guidance system gets by without expensive range sensors like laser range finder and uses regular sonar sensors as they are used in parking assistance systems in the automotive industry. An extra "sensor" which is used for position estimation is an RFID reader. These devices are commercially available for prices starting at 100 Euros.

The additional cost for the smart floor will amount to 13 to 15 Euro per square meter. If one compares these additional cost to the cost for expensive range sensors, then 1000 square meters of smart floor cost approximately as much as four laser range finders, which allows to equip two vehicle with range sensors yielding for example a 360 degree planar view or some non-planar view configuration.

The two key components of RFID based Robot Navigation on a Smart Floor outlined in the preceding section will be described in somewhat more detail below. Furthermore two specific service robot systems, using RFID based robot navigation will be described.

3.1 RFID makes the floor smart

The core idea of the Smart Floor is to distribute and integrate RFID transponders in the floor in an area-wide manner and use the transponders for various purposes.

Since the integration in the floor covering itself would complicate the manufacturing and increase the price of the floor covering and would have to be implemented separately and specifically for every type of floor covering, our partners Vorwerk Teppichwerke and FutureShape have been developing a so-called *Smart Underlay* (see Fig. 1). The smart underlay is separate meadow-like textile, in which the RFID transponders are integrated typically in a regular grid. This underlay can be placed nearly below every non-metallic floor covering. The material has furthermore an acoustic insulation effect. At the IT fair CeBIT 2006 in Hannover, for example, smart underlay was placed below wood (laminate), plastic, tiles, and carpet. Together with the floor covering on top of it the smart underlay forms the so-called *Smart Floor* (see Fig. 4).

The operation principle of RFID transponder is as follows. A reading device (reader) creates an electro-magnetic field over an antenna. RFID transponders located in this field will be charged by the emitted energy and enables to respond with an electro-magnetic echo. This echo typically carries an identifier plus various information such as co-ordinates, traffic information, environmental information, service information and alike, which is received by the reader. Transponders cannot only be read but also be written with information.

The piece costs for transponders basically depend on the storage capacity. The price per tag is currently around 0,30 to 0,50 Euro. Due to very tight competition a decay of this price to approx. 0,10 Euro per transponder is not unlikely.

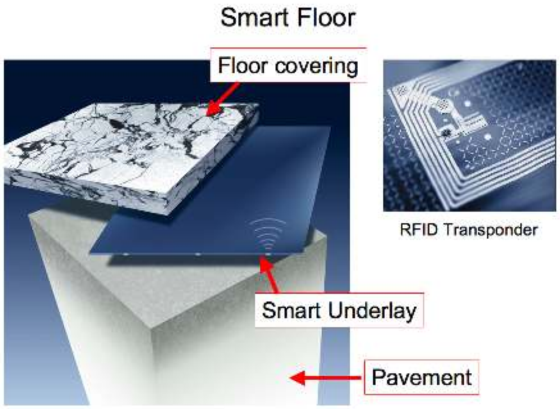

Fig. 1. Design Smart Underlay and Smart Floor

The RFID tags integrated in a smart underlay or a smart floor can serve various purposes:

- They can be used for position estimation and tracking of robots as much as of humans moving in large facilities such as warehouses or public buildings.
- They can store location specific information regarding the execution and performance of a service. For example, one could store the date of the last cleaning service and the code of a specific cleaning liquid or procedure.
- They could store information concerning the guidance of robot vehicles such as speed limits, temporary or permanent restricted areas.

- They can provide the localization infrastructure for any arbitrary location-based service in a large facility.

It is worth noting, that location-based information regarding the environment and the objects therein comes with absolute position accuracy. This property allows one to fuse and integrate the perceptions of many robots with many different sensor suits over time in a central map. Through this integration of time and the perceptions of many robots an increasingly accurate and complete image of the environment arises. All robots can access this central map ”for free” and at any time and use it for safe locomotion and execution of their mission. The RFID readers, which are used to read the information stored in the tags, quasi serve as additional, low-cost but highly accurate sensor.

In the extreme case, a robot could navigation almost blindly only by using its RFID readers, the RFID transponders, and the central map. This, however, requires the information in the central map to be up to date and to represent a correct and complete image of the environment.

These features do not only contribute to an increased reliability and accuracy but also have a significant effect on the implementation of a low-cost service robot system. The generation of a sufficiently accurate central map, requires, if at all, only a very small number of robots with precise and expensive sensors such as laser radars or stereo cameras. All other robots can be equipped with less accurate, inexpensive sensors such as sonars, infrared, or tactile sensors, since they can complete their environmental perception by the information in the central map. Over time and over many observations the integration and fusion even of inaccurate sensor data yields an increasingly accurate model of the environment.

3.2 Self-localization on a Smart Foor

A robot that uses RFID transponders for planar self-localization may be equipped with one or several RFID readers each having one or several antennas. Operating several antennas from one reading device can be facilitated by time-multiplexing. Any antenna is directed towards the floor. Obviously, a large antenna lobe allows for reading all transponders from a large area but each at a small spatial resolution and a small antenna lobe allows for the opposite.

Single point observations

Let the spatial resolution of transponder observation be high enough to allow for estimates as single points in robot coordinates. Also, it is assumed that at most one transponder can be seen at any moment and transponder observation does not provide any directional information. These assumptions correspond to a ”point-shaped” antenna.

When the robot moves for a certain time or distance, it records all transponder readings in one local map. Whenever self-localization is invoked, the local map is matched to a global map of the smart floor. The global map contains the positions of all transponders in world coordinates.

Self-localization under the present conditions admits the computation of the position only. The orientation is inferred from the robot odometry.

The present map matching is nothing but point cloud matching with the correspondence problem being trivially solved since transponder identifiers are unique.

Translation and rotation of the local map to the global map adhere to the least squares approach

$$\min_{\varphi\in[0,360^o),\,\vartheta\in I\!R^2} \sum_{i=1}^{n} ||T_i^{world} - (Rot_\varphi T_i^{robot} + \vartheta)||^2. \tag{1}$$

The summation index n equals the number of transponder observations, with multiple observations of the same transponder being handled as observations of different transponders with possibly the same coordinates. T_i^{robot} and T_i^{world} are the coordinates of transponder i in the robot and the world frame respectively. The translation vector ϑ may vary unboundedly in the plane and the rotation is denoted by a standard rotation matrix Rot_φ.

The optimal rotation angle is computed from two candidates values. The first value is $\varphi_1 \in [0, 180^o)$ with

$$\tan\varphi_1 = \frac{\sum_{i=1}^{n} det(T_i^{robot} - \bar{T}^{robot} \quad T_i^{world} - \bar{T}^{world})}{\sum_{i=1}^{n} (T_i^{robot} - \bar{T}^{robot})^t (T_i^{world} - \bar{T}^{world})} \tag{2}$$

if the denominator is different from zero, else $\varphi_1 = 90^o$ and the second candidate angle is $\varphi_2 = \varphi_1 + 180^o$. The superscript t denotes the transpose of vectors and the superscript $^-$ denotes average vectors.

The optimal rotation angle is obtained from value insertion as

$$\varphi_0 = \arg\min_{\varphi_j} \sum_{i=1}^{n} ||T_i^{world} - \bar{T}^{world} - (Rot_{\varphi_j} T_i^{robot} - \bar{T}^{robot})||^2 \tag{3}$$

and the optimal translation vector is $\vartheta_0 = \bar{T}^{world} - Rot_{\varphi_0}\bar{T}^{robot}$.

Position and orientation of the robot frame are eventually transformed into the world frame by

$$P^{world} = Rot_{\varphi_0} P^{robot} + \vartheta_0 \tag{4}$$

$$\varphi^{world} = \varphi^{robot} + \varphi_0 \bmod 360^o. \tag{5}$$

Single line observations

A suitable antenna shape for mobile robots is that of a rod antenna or a slim rectangle that comes close to a rod. The antenna is mounted crossways to the machine direction and it should extend over the whole robot width. The latter results in a high likelihood to observe all transponders that are overpassed.

A straight robot motion is considered first. Whenever a transponder is traversed, it can be assumed to lie on a line segment that indicates the rod position at the observation moment. All the segments are parallel since the motion is straight. The distances between successive observations of transponders $i-1$ and i are recorded as $D_{i-1,i}$, see Fig. 2.

The observed distance between transponder traversals being directional rather than Euclidean distances between transponder positions allows to compute the robot orientation in world coordinates. Let the robot make n transponder traversals along one straight line. Its direction in world coordinates is a solution of the minimization problem

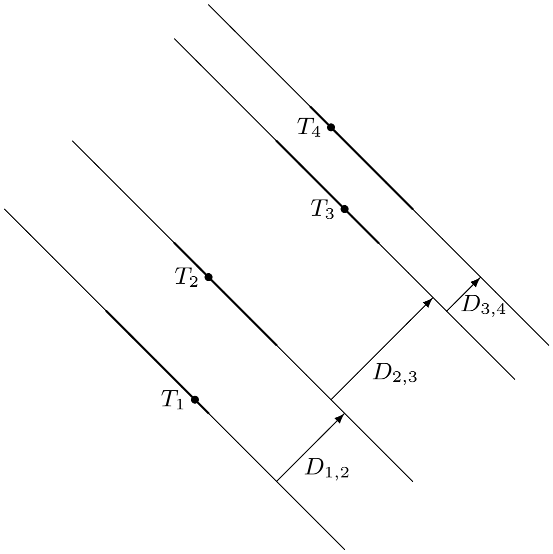

Fig. 2. Straight robot motion with transponder overpasses in the order $1, 2, 3, 4$ with successive distances $D_{1,2}, D_{2,3}, D_{3,4}$. The rod positions (bold segments) on the parallels are unknown and the exact positions of the transponders relative to the rod positions are unknown.

$$\min_{\varphi \in [0, 360^o)} \sum_{i=2}^{n} \Big((\cos\varphi, \sin\varphi)\,(T_i^{world} - T_{i-1}^{world}) - D_{i-1,i} \Big)^2 . \tag{6}$$

This problem can be solved numerically by iterated bisection. The robot position is not unique with respect to the observations but it can be narrowed down to a segment such that all projected transponder positions fall in that segment.

From this segment, the center of gravity of all projections can be chosen as position estimate of the robot while it observed the first transponder. The current position in world coordinates is then inferred as in the foregoing section. The approach can be extended from motion along a single line to other paths, in particular to parallel lines as they are typically used by cleaning robots.

4 Field Evaluation

The results of a first quantitative evaluation of the position estimation performance of our approach is shown in Fig. 3a). For this evaluation a test arena of 4 m × 3 m was set up, with RFID tags laid out in intervals of 50 cm. Within this test arena the robot was sent on a rectangular course for about 10 minutes at a speed of approximately 30 cm/sec. During the experiment the robot traveled approximately 170 meters. The position was estimated approximately every 200 millisecond or every 5 to 6 cm. As can be seen in Fig. 3a), the trajectory fitted to the estimated position forms a smooth path.

In Fig. 3b), the error between ground truth position and estimated position is shown. Ground truth was obtained by means of a specifically designed measuring system involving a laser range finder, which of course also contributes some error to the measurement. In the diagram in Fig. 3b) we can see that there is some significant position errors in the beginning of the experiment. Such significant errors occur only during the initialization phase of the algorithm. Once the system has the first fix, the errors drop drastically. It is also worth noting that the error in the described experiment stayed within bounds defined by the tag distance and the reading distance of the RFID reader. This, however, is not a guaranteed bound. If the reader does not discover a tag for a longer period of time, the position error might as well grow beyond this bound.

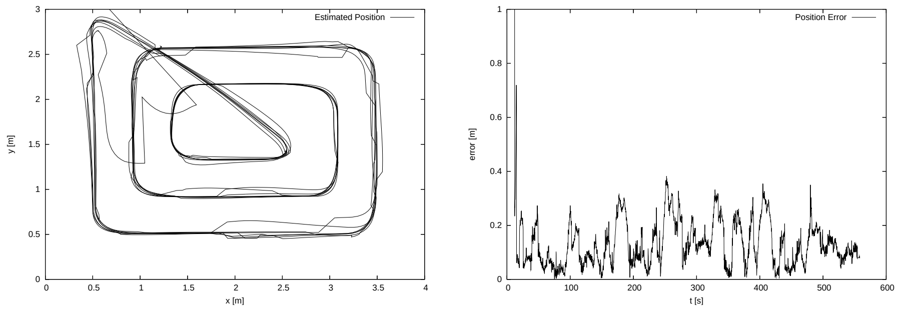

Fig. 3. a) Positions estimated along a rectangular course over a traveled distance of approx. 170 meters; b) Position error between ground truth position and estimated position

The RFID based navigation system described in this paper has matured to a level which allows and suggests excessive field testing. Three cleaning robots equipped with prototypes of the navigation system have been demonstrated during the international IT fair CeBIT 2006 in Hannover (see Fig. 4). During this exhibit the robots were in operation for approximately 6 to 8 hours per day, seven days long. Occasional mulfunctions of the robots were due to mechanical problems and problem with the collision detection sensors. The RFID navigation component itself worked without any problems. Currently an extended field test and a permanent installation of a smart floor in a gym and a cleaning robot navigating with RFID is in preparation.

Fig. 4. CeBIT 2006: first field tests for RFID based navigation of robo40 cleaning robots.

5 Conclusion

We have presented a novel position estimation system for mobile service robots using RFID transponders in a so-called smart floor. The approach has several advantages over existing solutions. It provides absolute position accuracy over arbitrary distances at low-cost. The sensor(s) needed for absolute position estimation are one or more RFID reader devices at price of 50 to 200 Euro each (depending on range and frequency). Additional features and advantages are easy installability and moderate installation cost, flexibility, and a spectrum of functions provided by the programmable smart floor.

Altogether the described RFID based robot navigation system has the potential not only to revitalize but to boost the technology and the stagnating market in the field of automatically guided transportation vehicles for industrial applications as much as the development of mobile service robots for professional applications.

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