IEEE Int. Symposium on Industrial Electronics, Guimarães, Portugal, July 7-11, 1997

Docking of a mobile platform based on infrared sensors

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Abstract – **This paper presents a sensor based docking strategy for a non holonomic mobile platform used to support material transportation operations in industrial like environments. A low cost infrared sensor system was designed and implemented, aiming at locating the mobile platform relative to the docking station where passive reflectors are installed. With this information, trajectories are generated and followed, docking the platform with a good accuracy (around $\pm 0.5cm$ in x and y, and $\pm 1°$ in θ), considering that the system was designed based on low cost sensors. The paper presents relevant experimental results.**

I. INTRODUCTION

Material transportation and handling is a major component in many industrial processes. The commonly used Automated Guided Vehicles (AGVs) do not yield flexible transportation solutions, given that the vehicles follow fixed and pre-defined sets of paths. Mobile robots, on the contrary, have the ability to travel freely on all empty space of an environment, giving the adequate support for flexible transportation systems. The flexibility is achieved through more complex navigation systems and more powerful sensors.

A particular problem raised upon the use of mobile robots for material transportation is the docking procedure, where three variables (position and orientation) have to be controlled in a 2D space, while, with AGVs, only one variable (position along a track) has to be considered.

This paper presents a docking procedure for a non-holonomic mobile robot (Fig. 1) based on a low cost sensorial system. The proposed methodology combines trajectory generation and following, together with a triangulation based localisation system.

From a rough initial estimate of the vehicle location, given by a human operator or by any other localisation system, e.g. dead-reckoning, laser and/or ultrasound based localisation, a minimum distance path is generated, under certain imposed constraints, aiming at driving the vehicle to a properly chosen vicinity of the docking station. This area is chosen in such a way that the two infrared (IR) scanners installed on the mobile platform (Fig. 2) are able to detect the two passive reflectors (Fig. 3) mounted on the docking station.

From this stage until docking is completed, the location of the mobile robot is always taken relative to the docking station. This is evaluated based on triangulation, using the two passive reflectors on the docking station and a pair of IR sensors located on the mobile platform to detect them. Sensor based motion is then used in an iterative process to successfully dock the vehicle.

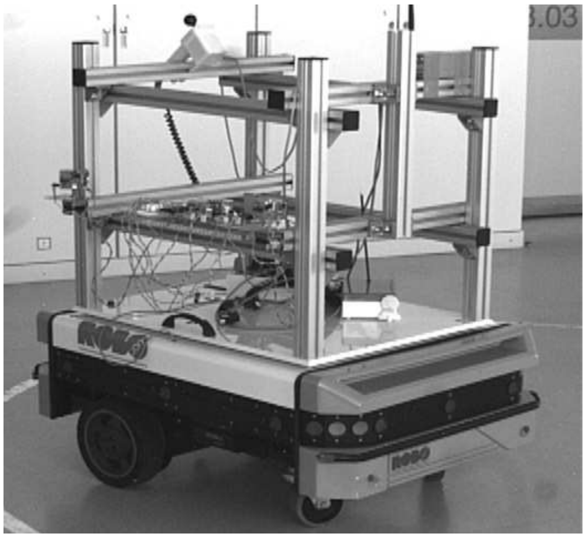

Fig. 1.: Mobile robot

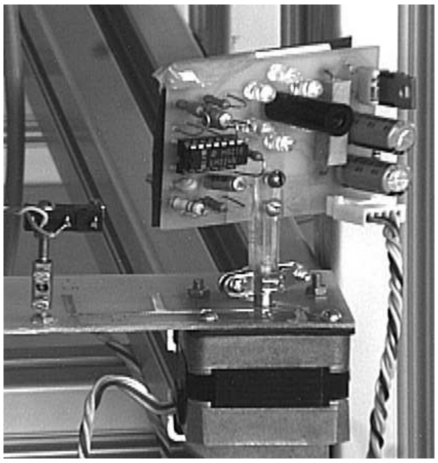

Fig. 2.: Infrared emitter/receiver

Since the docking procedure is to be applied on a non-holonomic vehicle, trajectories were designed as a sequence of straight lines and arcs of circle, respecting a minimum radius of curvature restriction.

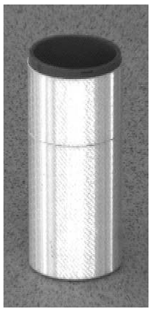

Fig. 3.: Retroreflector

The docking procedure described in this paper is one among a set of different modules under development on the PO-ROBOT (Multi-purpose Portuguese Flexible Mobile Robot) project. The project aims the implementation, in a commercially available mobile robot, of the main navigation and mission management functions with which the vehicle will safely operate in indoors structured or semi-structured environments. The system under development will be able to carry, on a point to point delivery basis, surveillance and material handling tasks in environments such as manufacturing facilities, hospitals and office type buildings. The remaining modules include path planning and obstacle avoidance, [15], obstacle detection, [7], localisation (see [10] for an ultrasound based localisation) and mission management, [16].

The paper organisation is the following: Section II describes the configuration of the experimental set-up. The implemented sensorial system and the associated signal processing localisation algorithms are described in Section III. Section IV describes the options taken for trajectory generation. Extensive experimental tests were conducted, some of which are presented in Section V, yielding good docking accuracy (around $\pm 0.5cm$ in x and y, and $\pm 1^o$ in θ). The achieved performance is particularly good considering that it is based on a low cost sensorial system, and that $0.5cm$ represents about 0.5 % of the platform's length. The paper concludes with the presentation of conclusions and directions for further work in Section VI.

II. SYSTEM CONFIGURATION

The experimental set-up is composed by a Robuter mobile platform (Fig. 1) and a sensorial system, along with two passive retroreflectors on the docking station.

The Robuter mobile platform is 102.5 cm long and 68.0 cm wide, weighting about 150 Kg. It is driven by two rear propulsive wheels powered by two independently controlled 300 W DC motors, and has two front free wheels, [13]. Its onboard computer is based on a 68020@16MHz Motorola processor running a real time operating system – Albatros – specifically developed for this platform, [11], [12]. It has a VME bus and four serial ports (RS232).

The sensorial system is composed by two IR emitter/receivers mounted on top of stepper motors and two passive retroreflectors on the docking station. The control of the stepper motors is achieved through a PIC microcontroller, [8], [9], that communicates with the 68020 main CPU through a RS-232 link. Fig. 4 presents a schematic representation of the the experimental set-up. Each reflector is made of a 15 cm long piece of a 4 cm diameter plastic pipe, wrapped in retroreflective tape.

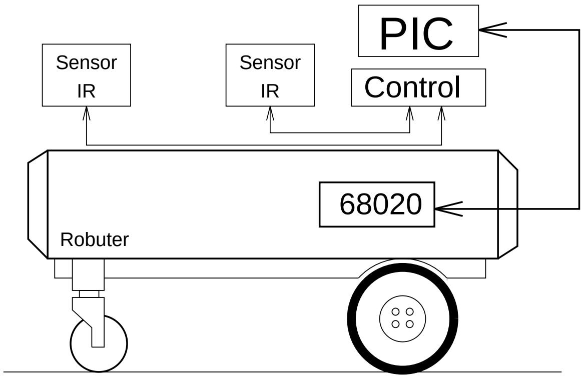

Fig. 4.: System configuration

The implemented docking methodology was tested and proven with two IR sensors, mounted on the right hand side of the mobile robot. Both the microcontroller and the implemented algorithms are prepared to a more general situation where docking could be done on both sides of the vehicle. This would be possible if two extra sensors were mounted on the left hand side of the platform, allowing sensor readings to be made in any direction.

III. SENSORIAL SYSTEM

Docking was implemented as a two-step procedure. On the second one, a sensor based motion methodology, having the docking station as a reference, was implemented. Therefore, a sensorial system was designed and built, so that all the information needed to determine the mobile robot's position and orientation relative to the docking station could be provided to its on-board computer.

Having this work been done in the framework of the PO-ROBOT project, the cost constraint and the desired docking accuracy were trade on the choice of the sensors.

Because a location relative to the docking station was needed, an odometry based absolute localisation system was not suitable, since it would exclusively rely on internal data, with errors accumulating over time. A sensorial system providing external data should then be used for the docking procedure. On the other hand, vision and image processing systems, eventhough satisfying the specifications required for docking, are expensive and demand high computational resources, [2].

IR systems, being cheaper than laser and requiring simpler technology, seemed an obvious solution. The low cost restriction lead to a sensor system based on passive beacons at the docking stations, keeping all the active components of the system on the mobile platform. Any kind of signal source outside the platform was thus rejected, [2].

The chosen system is composed of two passive retroreflectors, located at known positions relative to the docking point, and a pair of IR emitter/receivers, each of them mounted on a stepper motor, the whole system being controlled by a Microchip microcontroller (PIC 16C74).

The emitter consists of a simple set of IR LEDs, driven by a power transistor which is fed with a rectangular signal of known frequency and low duty cycle, generated by the PIC microcontroler, keeping the average current through the LEDs under a maximum of 100mA.

The IR receiver is described by the five functional blocks represented in Fig. 5. The low cost IR phototransistor is immediately followed by a pre-amplifier which boosts the signal to a level high enough to feed the filter with a satisfactory S/N ratio.

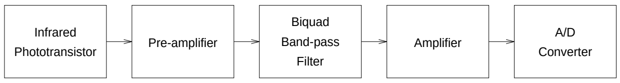

Fig. 5.: Functional blocks of IR receiver

Three op-amps implement the biquad band-pass filter, tuned to the frequency of the IR emitter (see Fig. 6), [14], [18].

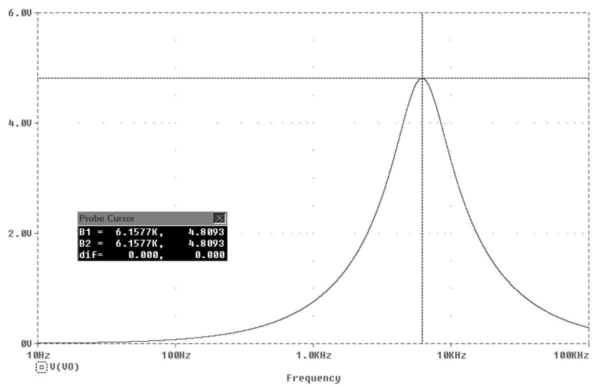

Fig. 6.: Simulated biquad filter response

Finally, the amplifier adjusts the signal to an adequate range, so as to cope with the PIC microcontroler built-in ADC input level, and also compensates, with a logarithmic amplifying factor, for the exponentional energy decay with increasing distance. As each of the stepper motors turns around, readings are made at each step thus filling the reading vector (see Fig. 7), that will be further analysed. In this figure the two angles with which the two reflectors were seen from the sensors are clearly represented.

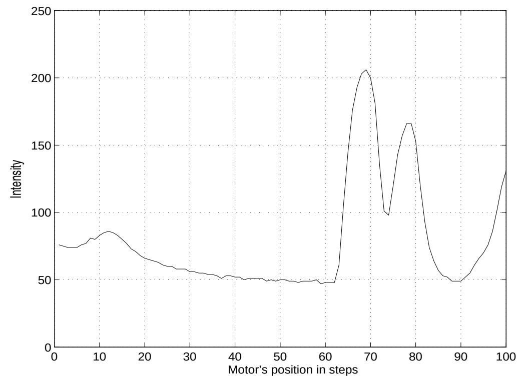

Fig. 7.: Sensor reading (Position in steps)

The microcontroler handles the signals sent to the stepper's drivers and to the IR emitters, and gathers the IR receivers' reading vectors, that are in turn sent to the mobile robot's main CPU, where further analysis is carried out.

As shown in Fig. 4, the PIC works as an interface between the platform's on-board computer and the IR sensors. The request for environment scanning and data gathering is issued by the 68020 and sent to the PIC by means of a set of commands developed for the communication between the two processors. In turn, it is the PIC's job to control the IR sensors and to return the requested data.

The signal processing procedures aim at estimating the four angles (a1, a2, b1 and b2 in Fig. 8) that represent the relative geometry of the mobile platform and the docking station, based on the readings from the sensors.

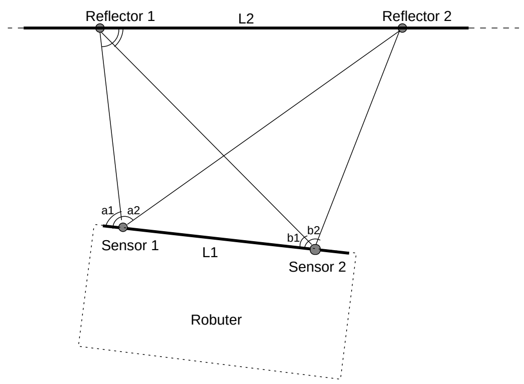

Fig. 8.: Geometric configuration of sensors and reflectors

A delay effect was observed when taking a reading with the sensors, due to the slow electronics response. This delay is a nonlinear function of the stepper motor angular velocity and of the energy of the reflected signal, its prediction being very difficult. To correct this effect, two readings are made by each sensor over the same angular area, one clockwise and the other anticlockwise (Fig. 9).

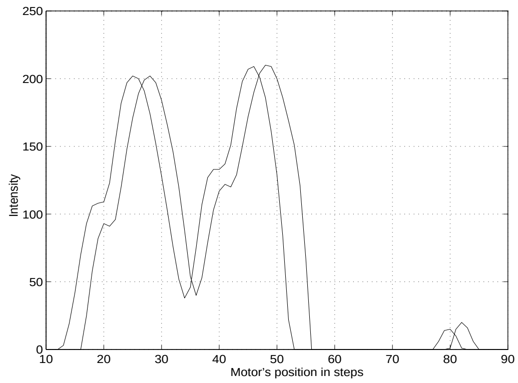

Fig. 9.: Clockwise and anti-clockwise readings for the same sensor

For both the clockwise and the anticlockwise reading vector three local maxima are determined, using a figure of merit for each local maximum in the vector. This figure of merit is an heuristic function that represents the likelihood of a certain peak being generated by a reflector. The reason why three maxima are determined, instead of just two corresponding to the two reflectors on the docking station, is that it is possible to have noise generating peaks, sometimes very similar to those from the reflectors (e.g., a narrow strip of intense light). A subsequent validation procedure tries to match maxima from the two vectors, using geometrical knowledge of the system, namely magnitude relationships between the angles. After the two correct maxima of both clockwise and anti-clockwise vectors are determined and matched, an average of their corresponding angular position is calculated, thus correcting the delay effect. Note that this effect is symmetric in the two readings, because they are both taken from the same position at symmetric angular velocities.

The so obtained four angles (a1, a2, b1, b2 in Fig. 8) – two from each sensor – are the input to a triangulation procedure that evaluates the position and orientation of the robot, relative to a frame defined on the docking station.

With the configuration represented in Fig. 8, three angles generally yield a non unique location solution, [17]. The four available angles provide redundant information that allows an evaluation of the quality of the estimated location. In fact, this redundancy allows the evaluation of the distance between the reflectors and the comparison of the estimate with the actual value, validating the measured angles. If validation fails, the readings are discarded and odometry is used until a valid reading is obtained.

Mobile robot's location based on triangulation is extremely sensitive to errors in the measured angles. If the stepper motors are not aligned with the platform's referential, biasing the measured angles, there will exist a very significant error in the so determined platform location.

In order to reduce the effect of biased readings on localization estimate, a calibration procedure was implemented. First, several measurements of the full set of angles are taken at different platform locations and orientations. For each of these measurements an estimate of the distance between the two reflectors is computed, as if the measured angles were correct. This estimate can be compared with the known value, L2 (Fig. 8). An error function of two variables (one for each sensor bias) that depends on the misalignment of each sensor, was defined as being the sum of the squared error of each estimate. In order to minimize this error function, the steepest descent method with adaptive step was used, starting from the point of zero misalignment. The step is increased if there are two consecutive evolutions of the solution in the same direction and decreased otherwise, [1], [3]. With this method, an estimate of the misalignment for each sensor is computed, being used to correct future measurements. The effectiveness of this calibration procedure depends on the set of positions choosen for the initial measurements. To obtain good calibration parameters the chosen positions for measuring should span the full working space of the sensors, [17].

IV. TRAJECTORY GENERATION

The trajectory planning, [5], and execution is divided in two different stages. The first one, named as **approach**, takes an initial rough estimate of the platform's location within the environment, and drives it to a position where a sensor reading may be correctly done. Because the sensors were only mounted on the right hand side of the platform, it must always dock with this side facing the docking station. The generated trajectories on the approach stage will have to reflect this constraint.

Following the **approach**, the **docking** stage generates paths that take the robot to it's final docking point, with an orientation parallel to the docking station, based on the information gathered by the sensors. Both stages generate trajectories composed uniquely of line segments and arcs of circles respecting minimum radius of curvature.

The frame of the docking station has its origin in one of the reflectors, as shown in Fig. 10, that also represents the docking point and the platform's frame, [4].

The **approach** procedure (Fig. 11) is used when it is not possible to obtain a sensor reading, either because the reflectors are too distant or because the sensors cannot be directed towards them. Therefore, some knowledge of the current position and orientation (x_0, y_0, θ_0) is required so that a path to a new position, where the sensors can be used, can be generated and followed. In PO-ROBOT project, the information concerning the initial location for the approach procedure is inherited from the localisation module running on the on-board CPU. The referred trajectories lead to the approach point (X_{APROX}, Y_{APROX}) (see Fig. 11), which is farther from the docking station than the final docking point (X_{DOCK}, Y_{DOCK}), aiming at lowering the risk of collision due to errors in the initial estimate of position

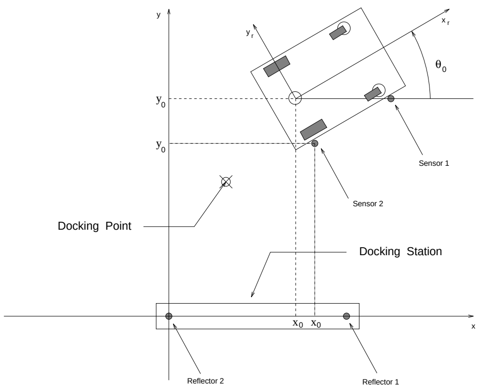

Fig. 10.: Docking station frame

and orientation. All paths generated at this stage start with an arc followed by a line segment and end with another arc, [6]. When the arcs have the minimum allowed curvature radius, this is the shortest path that leads the platform from a starting position and orientation to a goal position and orientation. It should be noted again the goal orientation at (X_{APROX}, Y_{APROX}) must allow a sensor reading. At the initial location, there are four possible movements: forward or backward, turning right or left (using left or right circunference). The arrival at the approach point can also be done in four different ways: moving forward or backward, in a clockwise or anticlockwise direction on the approach circunference. This results in 16 (4×4) possible trajectories. Since there are sensors only on the right hand side of the platform, only the 8 trajectories with the sensors directed towards the docking station are considered. The algorithm generates these 8 trajectories and rejects the ones including points closer to the docking station than the approach point (possibly collision trajectories). From the remaining, the algorithm selects and executes the shortest trajectory. See [17] for further details.

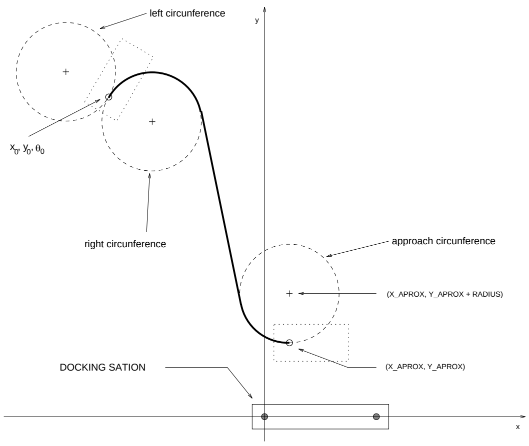

Fig. 11.: Illustration of an approach trajectory

The **docking** stage (Fig. 12) starts when it is possible to obtain a sensor reading, either at the initial location (x_0, y_0, θ_0) or at the approach point (X_{APROX}, Y_{APROX}) after the approach stage has been concluded. With the information from the sensors, an accurate estimate of position and orientation of the mobile robot relative to the docking station is computed through triangulation. The robot is then driven to the docking point (X_{DOCK}, Y_{DOCK}) along paths composed of two arcs followed by a final line segment [6]. One or both arcs can be skiped if it is possible to generate a path without them. A new reading is then made to ensure that the mobile platform has docked. This docking stage is repeated until a previously defined error has been attained.

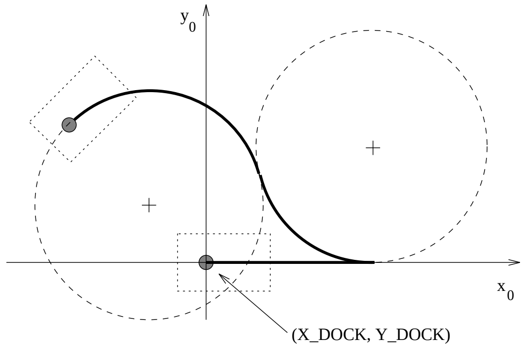

Fig. 12.: A docking trajectory

V. EXPERIMENTAL RESULTS

Several tests were conducted to study repeatability and performance. A few of them are herein presented, but a more extensive set of results is shown in [17].

Figure 13 represents a scaled version of the environment, the Robuter mobile platform, the docking station and the docking point. Ten different experiments were carried out. In all of them, the sensorial system was able to locate the platform relative to the docking station and therefore no **approach** stage was required.

The symbol ⊙> represents the location and orientation of the mobile platform at the beginning of the docking stage. Note that the platform's location is referred to the mid point between the two driving wheels. The first iteration drives the platform to a position within the represented ellipses, with the represented associated orientation. After the second iteration the robot's position lies within a 1cm diameter circle around the docking point and the orientation error is less than 1°, as represented in Figure 13.

From the fourth iteration on, there is no improvement in the obtained accuracy, as shown in Table 1, that shows statistical data of the error in location for 64 successive iterations, starting from the fourth in a normal docking procedure.

The displayed results show a good performance both in position and in orientation.

VI. CONCLUSIONS AND FUTURE WORK

A docking procedure for a non-holonomic mobile platform was presented including a low cost sensorial system

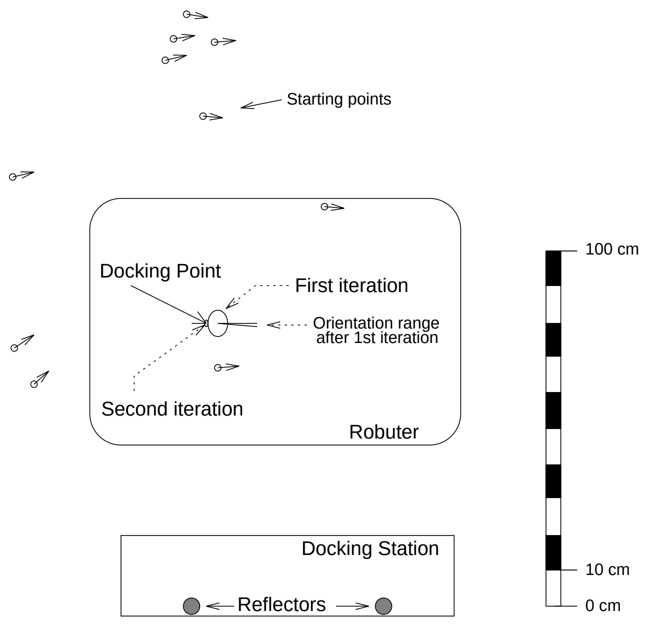

Fig. 13.: Experimental results of docking

Table 1.: Statistical analysis of error in location for 64 iterations of the docking procedure

	x_0 [cm]	y_0 [cm]	θ_0 [°]
Mean	-0.0128	-0.0370	0.0136
St. dev.	0.2045	0.1094	0.6066
Minimum	-0.5090	-0.3100	-1.4802
Maximum	0.4675	0.2456	1.6904

based on infrared sensors and a specially designed trajectory generator.

Considering the low cost of the sensor system, a very good precision was obtained. After the docking procedure, the final position and orientation of the platform is within $\pm 0.5cm$ in x and y, and $\pm 1°$ in θ of the docking point.

The system presents a good adaptibility considering that more sensors can be easily integrated with the current ones, without any changes on the control system. This would allow docking with any orientation and would also introduce redundancy in the sensor readings making the system even more reliable and precise.

Future work on the trajectory generator will be developed to allow navigation in an enviroment with severe movement restrictions, such as narrow corridors. With the integration of other sensors, for example sonars, an obstacle avoiding procedure will be incorporated on the trajectory generator aiming at providing docking facilities in the presence of unexpected obstacles in the vicinity of the docking station.

A detailed study of the kinematic and dynamic of both the platform and the scanner sensor system would make it possible to do faster readings and readings during robot motion.

VII. ACKNOWLEDGMENT

This work was partially financed by NATO Scientific Affairs Division on the framework of the NATO Science for Stability Programme, PO-ROBOT project.

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