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ODOMETRY FOR MOBILE ROBOTS WITH LASER SENSORS

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ABSTRACT

Autonomous mobile robots are dependent on systems for measuring covered distance to determine their actual position. Basically we are able to divide such systems broadly into two groups: First, in systems that rely on external references such as landmarks or GPS, and secondly in systems which collect robot-internal information, such as incremental wheel sensors. The soccer robots which are developed in the Department of Computer Application in Mechanical Engineering and the Department of Technical Mechanics at the Ilmenau University of Technology are representatives of the RoboCup Small Size League. They use measurement systems of both categories. Content of the article is the description of developing an additional measuring system on the basis of optical mouse sensors, which should increase the accuracy of determination robot position. Besides the technical aspects of the implementation of a sensor network consisting of three single sensors, also mathematical problems with respect to the analysis of measurement results, well as finally, first results of a previously realized prototype will be discussed.

***Index Terms* –** RoboCup, Optical Measurement System, Lasersensor, Odometry, Helmert Transformation, Coordinate Transformation, Microcontroller

1. INTRODUCTION

The present article deals with the development of an optical measuring system for measuring covered distances of autonomous mobile robots, based on laser sensors as they are used in computer mice. The measuring system will be used to improve the positioning accuracy of football playing robots. The mentioned robots are members of the Small Size League within the RoboCupSoccer Group. To achieve a better understanding of the initial situation, the article will start with a short introduction of the RoboCup Group inside the two departments Computer Application in Mechanical Engineering and Technical Mechanics at the Ilmenau University of Technology.

1.1. The RoboCup Initiative

"RoboCup is an international scientific initiative with the goal to advance the state of the art of intelligent robots." [10]

The original idea was to create a robot soccer team that would be able to win against a human team by 2050. Meanwhile, there are many different categories follow different approaches on mobile robotics. The presented football robots belong to the category of Small Size League RoboCupSoccer. For that League exist specific rules like the size of the playing field or the permitted robot hardware. The size of robots of the Small Size League is limited to a cylinder of 180mm diameter and 150mm height. [11]

The Departments of Computer Application in Mechanical Engineering and Technical Mechanics have decided for more than 15 years, to establish a RoboCup team in teaching. This allows a variety of different research areas for student training. So it is possible to work on tasks with a purely constructive nature, as well as solving problems involving complex mechatronic content. The integration of an additional measurement system for determining position in the existing robots requires not only structural adjustments but also solving mathematical, electronic and software-related sub-problems. These will be explained in detail.

1.2. Current Displacement Measurement

At the moment the position measurement is implemented using two independent measuring systems.

The first measurement system is realized by a video camera that is mounted above the playing field. Their images are evaluated on a Control-PC. The determined position of each robot on the playing field is interpreted as an absolute position on the field. That position is sent to each player over a wireless connection. Figure 1 shows a sketch of this system.

The second system is an incremental, robot internal measurement system. It is based on the measurement of wheel revolutions. This is achieved through incremental encoder on the motor shaft. The counted pulses are internally converted to robot corresponding distances.

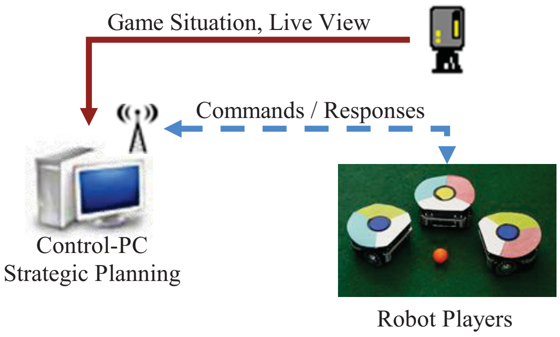

Figure 1: *Components of the Small Size League*

Both measurement systems are combined. Therefor the players get new starting positions at regular intervals by the control PC. The further position measurement, and thereby the determination of position, is based on the wheel encoders. Thus individual player can follow a given path of movement, for example a circle.

The incremental measuring system is above all at low speeds problematic. Here the motor torque is maximal and slip between wheel and ground is possible in situations of high acceleration. The calculated displacement differs so significantly from the actual distance traveled. An additional optical measuring system is to improve the accuracy of position determination in this cases. By combining the two robot internal measurement systems the player should be more accurate and can move independently from the camera system.

1.3. Motion Detection with laser navigation sensors

The considered optical measuring system operates on the basis of type ADNS-9500 laser sensors from Avago Technologies. The selection of that sensor type was carried out both in terms of technical parameters and on the basis of availability. Some of the technical parameters of the sensors are as follows [1]:

- Resolution up to 5040 counts per inch
- Motion detection up to 150 inch per second
- Digital interface via SPI

The principle of motion detection used by laser sensors is an evaluation of two consecutively recorded images. The surface is illuminated by a laser diode. The reflected light is recorded by a CCD sensor (in our case, 30 x 30 pixels). A digital signal processor determines the direction and amount of displacement between two images by calculating a two-dimensional cross-correlation. These values can be read as increments in X-and Y-direction. Because the set resolution is known, counted increments can be converted in distance units.

The sensors used are circuits that have already incorporated most of the required components. Only a few electronic components and an optical lens are necessary to take the sensors in operation.

2. CONSTRUCTION OF A PROTOTYPE

2.1. Hardware components

The construction of a first prototype of the optical measurement system was content of a student's work [2].

The work ask the requirement that the measurement system should consist of at least two separate sensors. This requirement resulted from the construction of the soccer robots. The robots have three drive wheels (see Figure 6). The drive wheels itself are composed out of 24 sub-wheels. For this reason the robot can move in any direction and revolve around any vertical axis. This is a huge advantage for the mobility of the robot. But for an optical measuring system this means, that not all states of motion can be detected. For example, a single sensor cannot detect a rotation around its optical center. But if the measurement system extended to at least two single sensors, at least one sensor is detecting a movement. The measuring signals of each single sensor should be recorded and processed by a microcontroller. For testing purposes an evaluation board, the MCBSTM32C from Keil, was provided.

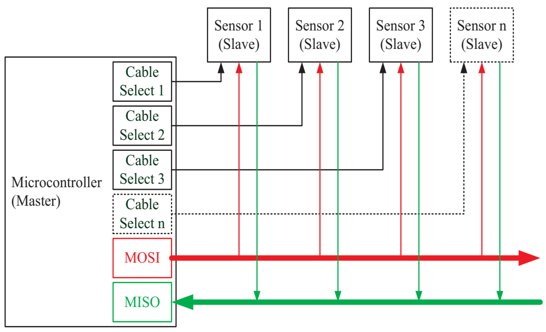

Figure 2: *Bus structure of the sensor array [2]*

Since the system should consist of at least two sensors, the question arose after connecting the sensors to the microcontroller. As already mentioned, the sensors come with an SPI interface. A direct connect would have been theoretically possible since the microcontroller (STMicroelectronics, STM32F107, Cortex-M3, ARM) has three independent SPI interfaces [9]. But these were already used for other peripheral modules of the evaluation-board. Furthermore an extension of the measuring system on more than three sensors not has been possible in this case. Finally a star network topology was used. Figure 2 shows this structure. From these requirements, a circuit was designed, which can connect up to three single sensors together. Over a connector system, the individual boards can easily be placed behind each other. Through jumpers each board is assigned a unique ID. In Figure 3 you can see the prototype of the sensor array.

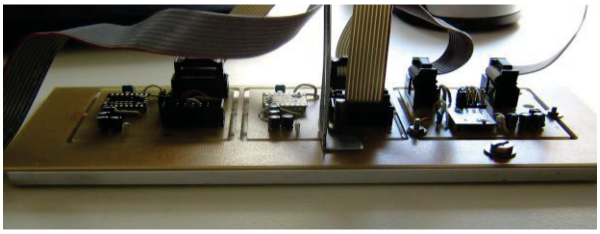

Figure 3: *Sensor Array*

With this demonstrator, initial tests have been performed.

2.2. Microcontroller software

To read and analyze the sensor data, initially a program for the microcontroller had to be written. This was done in the programming language C. Since the evaluation board provides a graphical display in the beginning all results has been shown on this display. Later the program was supplemented by features that can send the results via a serial interface to a PC.

To learn about the functioning of the sensors and the implementation of the SPI interface, the program was initially designed only for the evaluation of one sensor. Only when this stage was stable and free of errors, the algorithms have been integrated, which are necessary for the calculation of motions on the basis of multiple sensor signals. In an exemplary screenshot is shown. The X- and Y-values are the increments since the last reading, the "Absolute"-values are the added increments since the last reset.

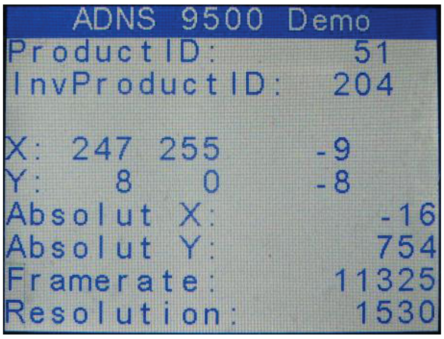

Figure 4: *Screenshot of a demo application*

3. MEASUREMENT RESULTS AND ANALYSIS

Once a working prototype had been built, first tests to determine the performance of the sensor were carried out. Initially the single sensors had been investigated. Subsequently it was investigated how well the combination of single sensors to a sensor array, the movement of the measuring system and thus the robot can detect later. The following section focuses first on the results of the single sensors.

3.1. Measurement results of single sensors

In order to be able to make statements about the accuracy and reproducibility of the sensors, different measurements were carried out. Therefore, the sensors were defined moved through a positioning machine. An "OWIS" positioning system with the following relevant parameters was used [6]:

- Linear resolution: 200 steps per mm
- Positioning speed: 2.5 mm/s
- Positioning error: 25µm/100mm

With the help of the positioning machine movements along the X-and Y-axis could be realized. A combination of both directions of movement is also possible. But a rotation of the sensors is not possible with such a system. Even the positioning speed of the machine is so small that the dynamic properties of the measuring system must be determined in later studies.

The following measurements were already carried out:

- One-dimensional motion along X-axis, 100mm
- One-dimensional motion along Y-axis, 100mm
- Two-dimensional motion along X- and Y-axis, 100mm in each direction
- Rediscovery of the zero position
- Direct comparison of the results of several parallel-powered sensors

Due to the low speed of the positioning machine, could only be a relatively small number of repetitions performed. Statistically reliable result cannot be deduced from it yet.

Figure 5 shows the measured values for the experiments with one-dimensional motion along the axes X and Y. The sensors were moved for a distance of 100mm. The sensor was set to a resolution of 1620cpi, which should lead to a theoretical value of 6378 steps for a distance of 100mm. Clearly you can see that the distance between sensor and ground plays only a subordinate role. This parameter has (within limits!) only a little effect on the result (standard deviation is always less than 0.2%). The conspicuous difference between the two axes is due to the lighting situation at the measuring station. Test with rotated sensors had shown similar results. But why the theoretically determined increments for the target position are not reached? It can be assumed that the adjustable resolution of the sensor is only a rough guide. This can also be seen from the fact that this value can only be changed in steps of 90 cpi. The actual value will vary with the lighting situation.

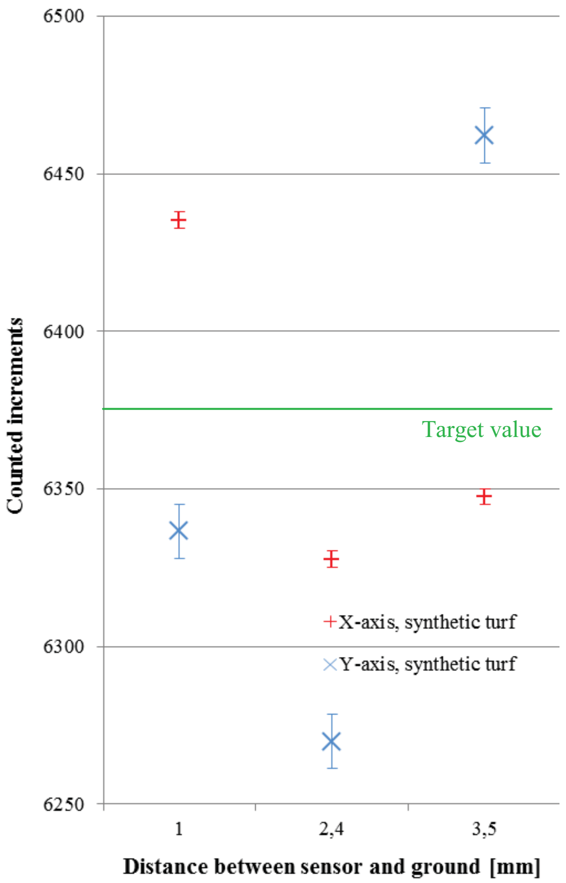

Figure 5: *Measured values and standard deviation*

In principle we can say that the individual sensors are able to ensure a very good reproducibility of results. Even without optimization of the light conditions, the standard deviation of the results was always less than 0.2%. The results of the combined movement in the X- and Y-direction yielded comparable results. Even here the value of standard deviation was approximately 0.1%. The sensors could convince in terms of accuracy. The fact of conversion errors from increments into path lengths has to be studied.

3.2. Transformation of sensor data

So far, only displacement values of individual sensors in the X- and Y-direction were considered. To draw conclusions from the individual values of the sensors on a motion of the robot, these values must be combined and transformed. In Figure 6 one recognizes the goal of transformation: Determination of the vector $\vec{r}$ and the angle φ out of the incremental values.

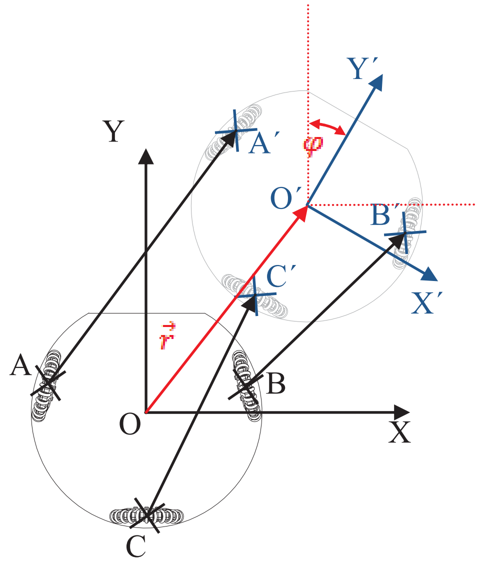

Figure 6: *Calculation of the actual movement*

From the old position of the robot with respect to the XY coordinate system, the new position can be determined. This results also into a new robot coordinate system X'Y'. This coordinate transformation is based on the displacement of the points A, B and C. The coordinates of A', B' and C' result from the sensor signals.

Under certain circumstances, it is possible to detect the shift of the XY coordinate system into the coordinate system X'Y' with only one sensor. This is the case if certain constructive measures prevent inappropriate motion states. Thus uses the robot project of the magazine “c't”, the “c't-bot”, no omnidirectional wheels. This is why the robot cannot rotate around any axis. By arranging the sensor outside the center of the robot, in each case increments can be determined [3]. The robots of the department of computer application in engineering don't meet these constraints. Therefore, at least two sensors are necessary.

The complete derivation of the Helmert-transformation to determine the new robot coordinate system can be seen in [2]. At this point is only the principle explained briefly. The coordinates of points A, B and C can be derived from the installation position of the individual sensors with respect to point of origin O. The point O is the point of origin of the old robot coordinate system. The coordinates of the points A', B' and C' result from the sensor data:

$\begin{pmatrix}\Delta X_A \\ \Delta Y_A\end{pmatrix}$, $\begin{pmatrix}\Delta X_B \\ \Delta Y_B\end{pmatrix}$ and $\begin{pmatrix}\Delta X_C \\ \Delta Y_C\end{pmatrix}$. These six points are referred as control points of the Helmert-transformation. The transformation equations of the Helmert-transformation are:

$$(I) \quad x = a + mX\cos\varphi - mY\sin\varphi$$
$$(II) \quad y = b + mX\sin\varphi + mY\cos\varphi$$

in which X and Y are target coordinates and x as well as y are coordinates of the old coordinate system. The transformation parameters are:

- a: translational shift of the coordinate origin in X-direction
- b: translational shift of the coordinate origin in Y-direction
- phi: angle of rotation between origin and target coordinate system
- m: scaling factor between origin and target coordinate system

(I) and (II) expressed in matrix-vector-notation:

$$(III) \quad \begin{pmatrix}x \\ y\end{pmatrix} = \begin{pmatrix}a \\ b\end{pmatrix} + m\begin{bmatrix}\cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi\end{bmatrix}\begin{pmatrix}X \\ Y\end{pmatrix}$$
$$(IV) \quad R\varphi = \begin{pmatrix}\cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi\end{pmatrix}$$

It can be simplified as follows:

$$(V) \quad c = m\cos\varphi$$
$$(VI) \quad d = m\sin\varphi$$
$$(VII) \quad x = a + cX - dY$$
$$(VIII) \quad y = b + dX + cY$$

By using three sensors, there are more control points than necessary. Through a correction calculation barycentric coordinates can be determined. A subsequent series expansion determines the modified parameters c and d. After that it is possible to determine the missing parameters.

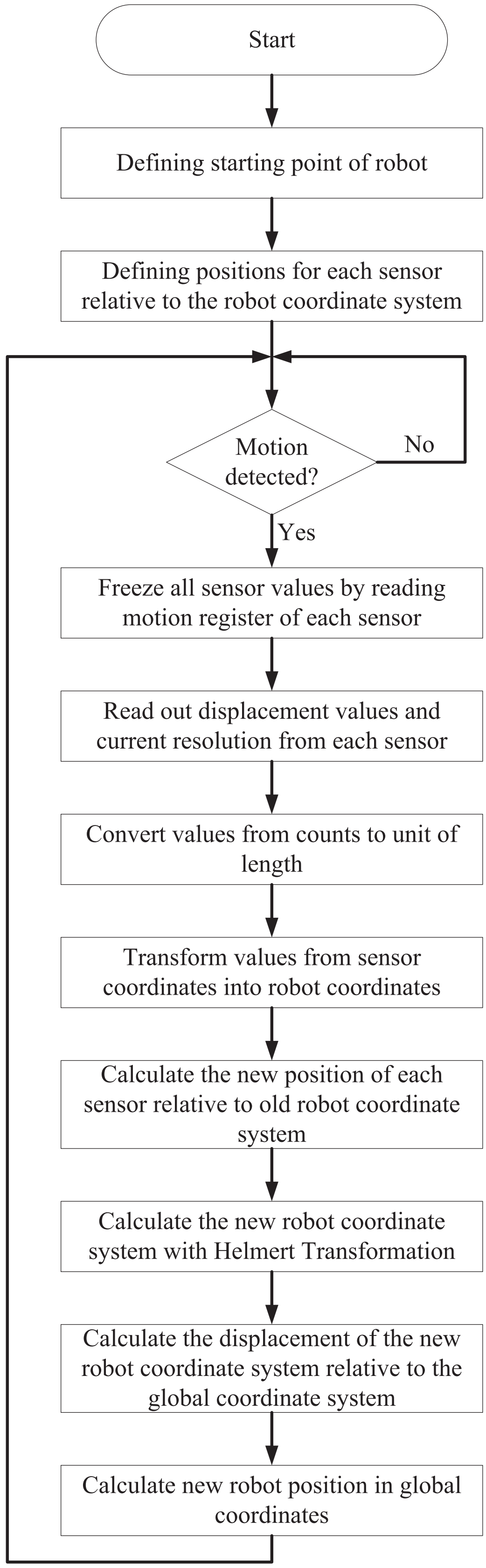

Figure 7: *Flow chart of the displacement measurement algorithm*

$$(IX) \qquad \frac{d}{c} = \frac{m\sin\varphi}{m\cos\varphi} = \tan\varphi$$

$$(X) \qquad \varphi = \arctan\left(\frac{d}{c}\right)$$

$$(XI) \qquad m = \sqrt{c^2 + d^2}$$

$$(XII) \qquad a = \tilde{x} - (c\tilde{X} - d\tilde{Y})$$

$$(XIII) \qquad b = \tilde{y} - (d\tilde{X} + c\tilde{Y})$$

The tortuous variables are the barycentric coordinates. The data flow of the entire algorithm for the determination of the new robot position is shown in Figure 7.

After the implementation of the algorithm for determining the position tests were again carried out. Since the positioning system is not allowing rotation movements, no defined tests of that kind could be done. Manually drawn curves but showed very good results. Further tests with the help of appropriate positioning machines are necessary.

4. SUMMARY AND OUTLOOK

The research on an additional optical measuring system for determining the position of soccer robots have shown, that it is possible with the aid of laser sensors building such a system. Initial tests with the ADNS-9500 sensors from Avago have shown very good results of the accuracy of these sensors. Due to the limited dynamic properties of the available positioning machine, studies about the dynamic properties of the sensors are still pending. It is still necessary to check the behavior of the algorithm for determining position using three sensors in the target system. From the perspective of a control program for the robot, it has to be investigated how the three positioning systems, camera, wheel encoders and laser sensor can support each other.

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