A Fast and Accurate Sonar-ring Sensor for a Mobile Robot

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Abstract

A sonar-ring is one of the most popular sensors for indoor mobile robots, because it is simple and gives omni-directional distance information directly. However, it is difficult to measure the accurate direction of reflecting points by a conventional sonar-ring sensor. Further more, conventional sonar-ring sensors are slow to get full 360 degrees information due to sequential driving of transducers for avoiding interference. In this paper, we propose a new sonar-ring sensor system for a mobile robot which can measure the accurate bearing angles of reflecting objects in a single measurement. The proposed system employs the measurement by using differences of time-of-flight and by simultaneous transmit/receive of all directions, and consequently achieved fast measurement. We implemented a prototype of the proposed sonar-ring on a mobile robot. The experimental data show the effectiveness of the proposed system.

1 Introduction

An external sensor is essential for a mobile robot to respond to its environment and determine its position. A sonar-ring is one of the most popular sensors for indoor mobile robots, because it is simple and gives omni-directional distance information directly.

In mobile robot navigation tasks, such as wall following, doorway traversal, obstacle avoidance and sensor based positioning, accurate reflection bearing information has been requested [1]. Also many research approaches on sensor-based path planning of mobile robots in unknown and complicated environment assume that robots are able to measure precise angle information [2]. In real robot navigation, not only accurate measurement but also fast measurement is an essential factor.

However, a conventional sonar-ring is regarded as difficult to measure accurate bearing of reflecting points due to wide directivity of ultrasonic transducers [3]. The use of narrower-beam width transducers for improving the bearing accuracy causes a dead angle because of specular reflection of ultrasound [4], and there is another problem of size because the narrower-beam transducers are larger. Furthermore, it is slow to get full 360 degrees directional information due to sequential driving of the transducers for avoiding interference. Consequently it has been difficult with the sonar-ring to realize robot motion in a relatively complicated environment, eg. doorway traversal [5].

On the other hand, ultrasonic sensing methods using multiple receivers or using wave shapes of the echoes have been researched for the localization of known environmental features [6] [7] [8] [9]. Those researches are usually based on ultrasonic waves characteristics – *specular reflection* [10]. With those method, an accurate bearing angle measurement can be achieved. However, those methods are limited to measure only in the area of the directivity of the transducer, so mechanical rotation of the sensor head is required when these sensor are used on a mobile robot, hence it takes time to measure the environment around the robot.

In this paper, we propose a method to provide fast and accurate bearing angle measurements. In this method, transmitters and receivers are placed on the circumference intimately and all the transmitters are driven simultaneously. Then, time-of-flight differences are measured by the receivers on the circumference to calculate the accurate bearing angle. As a result, it is possible to measure all the 360 degrees directions in a single transmit/receive cycle, and consequently possible to achieve fast measurement.

The biggest difference of the proposed method from driving all transducers of an ordinal sonar-ring [11], is that the directivity of the transducers are positively overlapping to measure the accurate bearing angle.

In the next section, we briefly explain the background of an accurate bearing angle measuring methods. In Section 3, we propose a new sonar-ring sensor. The experiment was performed to verify the potential of the proposed system. The result of experiments is shown in Section 4. The paper concludes with a discussion of further developments.

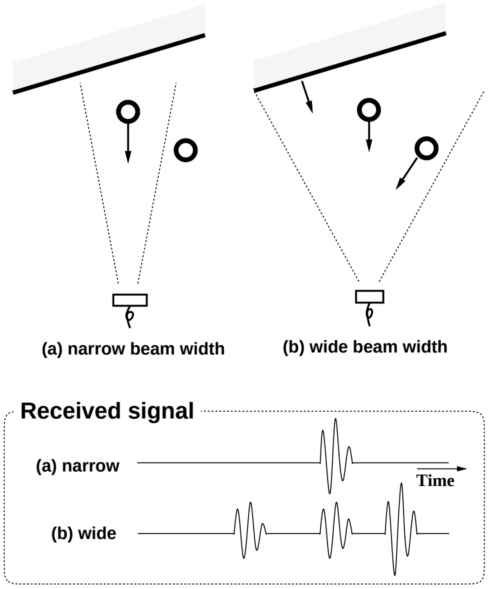

Figure 1: In case of using the wider beam width transducer, possibility of that multiple objects are in the beam increases.

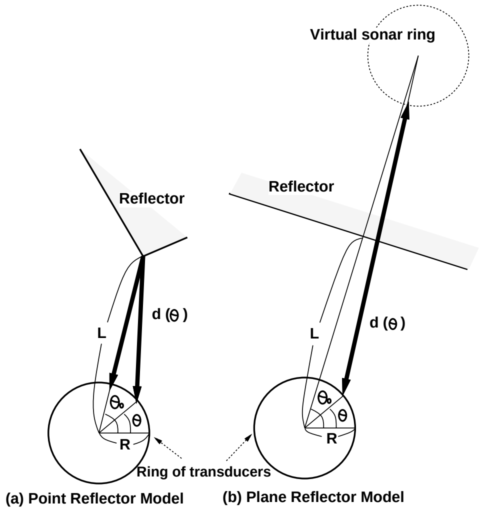

Figure 2: Ultrasound propagation pass models [10]. $d(\theta)$ denotes propagation distance. L is a distance between a center of the ring to a reflecting point. R is a radius of the sonar ring. θ_0 is a bearing angle to the reflecting point. θ is a bearing angle of a receiver.

2 Background – Specular reflection of ultrasound

The pulse-echo ultrasonic sensor is well known for its simplicity and low cost within robotics applications. It can detect easily the distance to a reflecting object. However the accurate direction to the reflecting object is not easy to measure with conventional ultrasonic sensors, since the direction of the object is estimated based on the heading direction of the transducer and the directivity of its beam. The directivity is about $30 \sim 60$ degrees and it is not sufficiently sharp to measure the direction of objects.

On the other hand, many objects in indoor environment can be assumed to be specular reflectors for ultrasonic waves, since wave lengths of ultrasound used in air are from 4mm to 20mm. Specularity implies that the reflection comes from a point, not from an area, and that the reflecting position is the surface of the wall which is perpendicular to the incident direction of a plane or curved surface, or a convex corner. Hence, if we can measure the accurate bearing angle of the reflecting point, useful informations as the bearing angle of the wall can be gotten.

The accurate bearing angle measuring methods of a reflecting point are proposed, which uses the propagation time differences of leading edges of the echoes which are coming back from the same reflecting object [7][8]. These methods accomplish bearing angle measurement which is more accurate than the beam width of the transducers. However, in case of using a single transmitter and two receivers, the measurable area is the overlapping area of the directivity of the three transducers, and it is not enough for robotics applications, so mechanical rotations were employed in past researches [7][8].

3 Proposal of a fast and accurate sonar-ring sensor

In this paper, we propose a new sonar-ring sensor which can measure the accurate bearing angles to reflecting points rapidly. With respect to the difference from a conventional sonar-ring sensor, the conventional sonar-ring is nothing but placing plural sets of imprecise ultrasonic sensors on the robot's circumference, however our proposed sonar-ring sensor uses all transducers at the same time and processes the received signals based on the assumption that the ultrasound reflection comes from a point.

3.1 Basic idea

The basic idea can be expressed in four steps :

- Transmit an ultrasonic pulse radially and simultaneously : Rapid measurement is achieved with the omni-directional transmission in a single transmit cycle.

- Receive the echoes with plural wide beam receivers on the circumference : Place the receivers to overlap their directivity, and measure differences of the propagation time of echoes (Fig.3). Each Time-of-flight (TOF) is measured by detecting the leading edge of the echo.
- Detect TOFs of multiple echo blocks for the each transmit at each receiver : Since, multiple objects can be within the wide beam of each receiver (Fig.1), all echoes should be detected by each receiver to achieve the measurement of these objects.
- Calculate the direction of reflecting points : Accurate bearing angle are calculated from the differences of TOFs.

This method achieves accurate and rapid measurements of the bearing angles to the reflecting points in all directions.

3.2 Technical method

3.2.1 Simultaneous transmission to radial directions

In this method, transmitting one ultrasonic pulse to all directions equally is required. However, conventional ultrasonic transducers on the market have specific directivities because of their shapes. There are a few special transducers or techniques which can transmit a pulse omni-directionally [12] [13], but they are not suitable for being mounted on the robot because of its big size or the insufficiency of power. Therefore, we propose to place wide directivity transmitters on the circumference intimately and to drive all the transmitters simultaneously. In this case, the resultant ultrasonic wave can be assumed as being emitted by a single point source located at the center in two dimensions.

3.2.2 Measurement of TOF with leading edge

For measuring the TOF of each echo signal, the easiest and most effective way is to detect its leading edge by a simple analog circuit with a threshold comparation. Since the proposed method is using the differences of leading edges among the different receivers, the accuracy of the TOF is very important in this method. Thus, even when a narrow-band transducer is used, the echo signal should be amplified in the base band and should reach the comparator directly without envelope detection. Compared with wave shape processing methods, the circuit and process of this method is simpler and smaller. Since the proposed method uses multiple receivers simultaneously, simplicity of each receiver is important to reduce the total amount of circuitry.

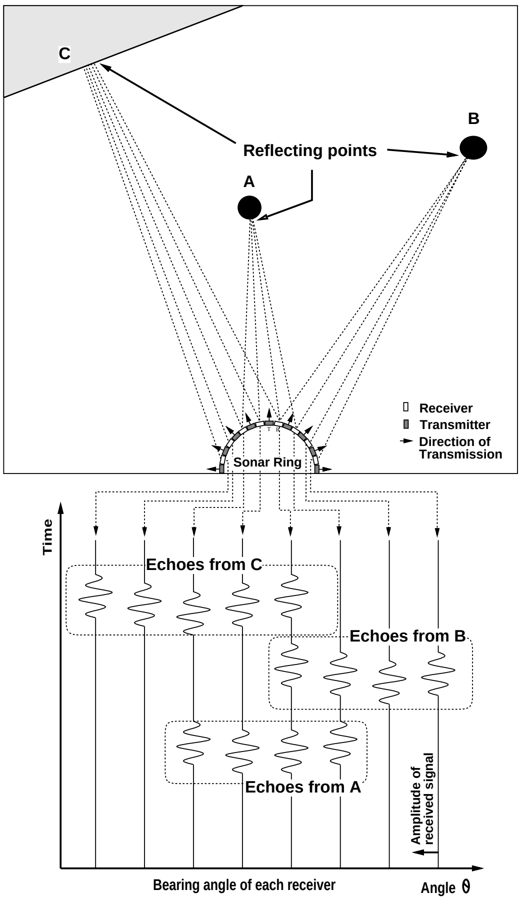

Figure 3: Relationships between reflecting points in an environment and observed echoes at each receiver. The bottom graph shows received echo signals at each receiver which are lined in bearing angle θ. The echoes coming back from a same object are appear close in time among close receivers.

3.2.3 Detection of multiple echoes

For the purpose of detecting objects in the full directions, it is necessary to detect echoes from multiple objects, not only from the nearest object in each receiver. After detecting the end of the first echo, the next echo can be detected by the same method as the first one.

3.3 Calculation of angle and distance

Based on the assumption that the reflecting object has the property of specular reflection, the propagation pass of ultrasound is modelized using the ray-tracing method [10] (Fig.2). Then we apply the model to the proposed sonar-ring. Transmitting an ultrasonic pulse to all directions is regarded as a trans-

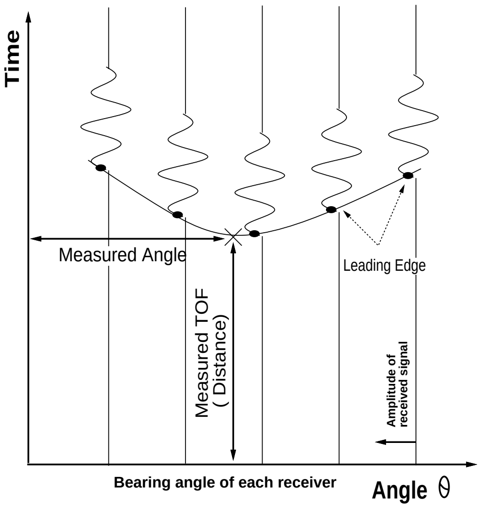

Figure 4: Measured bearing angle and distance are a minimum point of quadratic function fitted with detected leading edges. Bearing angle and distance are calculated using Formula (3).

mission from a single point source in two dimensions. Here, we assume that the reflecting object is located at direction θ_0 and distance L from the center of the sonar-ring.

Case I – A point reflecting object in two dimensions (eq. a corner edge of the wall): The propagation path of the ultrasound from the center of the ring to a receiver placed at direction θ via the reflecting object is modeled as shown in Fig.2(a), the propagation distance from transmitter to receiver is given as follows:

$$d_{point}(\theta) = \sqrt{L^2 + R^2 - 2LR\cos(\theta - \theta_0)} + L - R. \quad (1)$$

R is the radius of the sonar-ring.

Case II – a plane reflecting object : The propagation path can be considered using the mirror model as shown in Fig.2(b). The propagation distance is equal to the distance from transmitters of a virtual sonar-ring located at symmetrical point of the real receiver, and is given as follows:

$$d_{plane}(\theta) = \sqrt{2L^2 + R^2 - 4LR\cos(\theta - \theta_0)} - R. \quad (2)$$

Those formulas are approximated to Formula (3), when $L \gg R$ and $|\theta - \theta_0|$ is reasonably small, eg. $|\theta - \theta_0| < 45$degrees.

$$\begin{aligned} TOF(\theta) &= d_{approx}(\theta)/c \\ &= \frac{2(L-R)}{c} + \frac{LR}{c(2L-R)}(\theta - \theta_0)^2. \quad (3) \end{aligned}$$

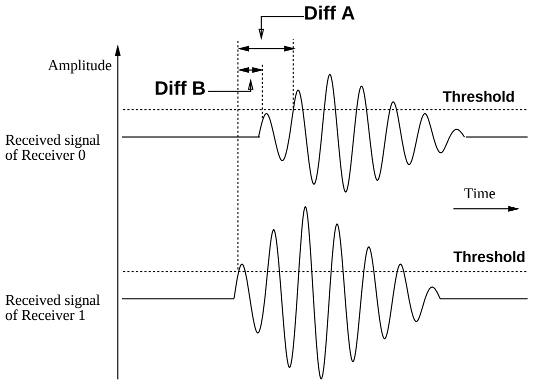

Figure 5: To measure the accurate bearing angle, the difference of the corresponding leading edges should be measured between the receivers (Diff B). The difference of the received echo amplitudes between the receivers causes the failure to detect the corresponding leading edges (Diff A).

where c is the velocity of sound.

Consequently, when the TOF for the same object are measured at several receivers, the distance and direction to each reflecting object are calculated by finding the appropriate values of L and θ_0 of Formula (3). The concrete processes are as follows.

3.3.1 Correspondence problem

The TOFs of echoes which were detected by all receivers should be classified into groups, one for each reflected object (Fig.3). For this purpose, TOFs measured at receivers are grouped by using the conditions that the difference of TOFs of the neighbor receivers are less than ε, at first. Here, with considering one wave length error which is explained in the next section, $\varepsilon = 1.25T + T_0$. Where T is one cycle time of the ultrasound wave, and T_0 is the TOF difference between two receivers. They are candidates for a TOFs group which are coming back from the same object. Then, those TOFs are checked whether they are coming back from the same object by fitting with Formula (3). If the data of the TOFs group do not fit with Formula (3), select those TOFs only which fit, and redefine the TOFs group which can be assumed coming back from the same object.

3.3.2 Calculation

Calculate angle and distance to the reflecting point by fitting TOFs of the same objects with Formula (3), and finding L and θ_0 (Fig.4). Fit the formula to TOFs

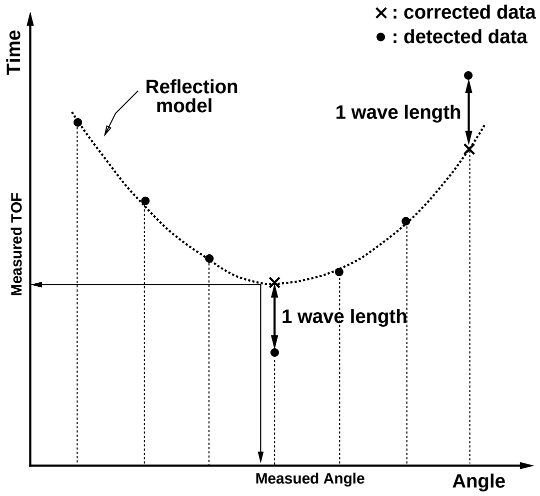

Figure 6: One wave length error detection using the reflection model. The error is discrete, one wave length, so it is easy to correct it by using the reflection model.

which are measured more than three receivers using the least squares.

3.3.3 One-wave-length error correction

In this method, the same wavefront of the reflected echo must be detected by different receivers when measuring the TOF using the leading edge, ie. for an example, the difference "Diff B" in Fig.5 should be detected. When the leading edges are detected with a threshold level, small amplitude difference at each receiver can cause one ultrasonic wave length detection error "Diff A", as shown in Fig.5. Since, this type of error is discrete as shown in Fig.5, the difference between "Diff A" and "Diff B" is almost equal to an integer times wave period. Therefore, it is easy to detect and correct a few wave length errors with a good reflection model when more than three receivers detect the echo (Fig.6) [14].

4 Experimental verification with the first prototype on a mobile robot

An experiment was performed to evaluate the potential of the proposed method.

4.1 Sensor hardware

The mobile robot with a sonar-ring sensor used in this experiment is shown in Fig.7. The size of the sonar-ring is 32cm in diameter and the transducers are placed on the circumference, which is 22cm in diameter and 50cm from the ground.

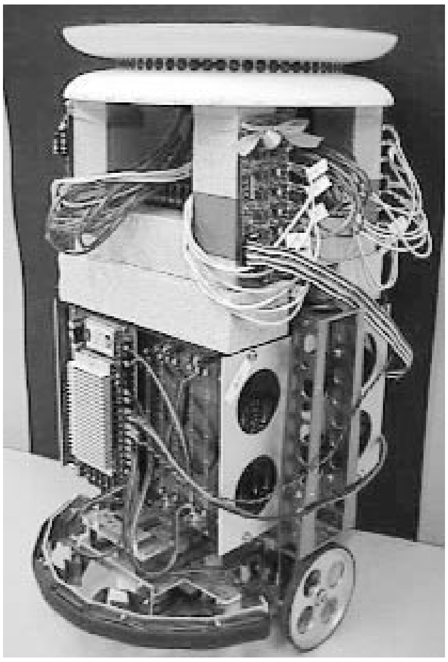

Figure 7: Robot used in this experiment. The sonar-ring sensor with 30 transmitters and 30 receivers is mounted on the top.

Piezoelectric transducers (Murata MA40S4R) are used because of their wide beam width. The size of the transducers is 1cm in diameter. 30 transmitters and 30 receivers are placed alternately on the ring, and they are fixed with a horn whose purpose is to avoid the reflections from the ground. Receiver type transducers are used for both transmitting and receiving for reducing the ripple of the received echo signal.

All the transmitters are connected electrically and are driven simultaneously. The transmission signal for each transmitter is an about 150V wide band pulse. The amplitude of the transmission differs about double in direction, but there are no differences of the phase. The typical received signal is 40kHz in frequency and has a duration of about 700 μ seconds.

All the 30 receivers are connected to individual amplifiers. They only amplify the base band echo signal without envelope detection. The amplified received wave signals go through the comparators with a threshold value which changes in time [15]. The outputs of the comparators which are binary signal per receiver are sampled and stored at the memory each micro-second in parallel and the data process is performed by software after getting all echoes.

The processing algorithm is as follows: (1) Find leading edges in the signals received by each receiver. Here, we use a threshold value in time axis. When the comparator output is low for a certain time after detecting an echo, we assume that the echo ended, and start waiting for the next echo (In this method, a leading edge of the next echo which overlaps with the duration of the previous echo can not be detected. Therefore, the reflecting objects should be spatially separated from each other.) (2) Correspond the detected leading edges to the object (Grouping). (3) Calculate bearing angle and distance by fitting the data to Formula (3), while also detecting the mentioned one wave detection error. In this experimental system, TOF differences between neighbor receivers are $10 \sim 30\mu$ seconds, and one wave length is about 25μ seconds. Therefore, one wave detection error compensation is important.

According to an experimental result with a columnar object at distance 1.5 m, maximum error of bearing angle measurement was ±0.8 degrees and RMS value of it was 0.41 degrees.

4.2 Experimental environment and result

Experiments using plane and columnar objects were performed (Fig.8). Columnar objects were 45mm in diameter.

Fig.9 shows the experimental result in a single measurement, which means this is measured by a single transmit/receive cycle. The robot is located at the origin of the coordinate axes. The experimental results show that the proposed sonar-ring sensor successfully measures the location of the reflecting points in the environment.

Next, the robot moves and stops at each 10 cm and performs a measurement in repetition. The result of measured reflecting points in this experiment is shown in Fig.10. The trajectory of the robot which is generated based on odometery data is along the y-axis starting from the origin of the coordinate system.

4.3 Discussion

The proposed method could achieve accurate omni-directional measurements in a single transmit/receive cycle. And also while the robot moves, movements of the reflecting points according to the motion of the robot are observed. The measured reflecting points on the columnar reflectors remained at the same points. The measured reflecting points on the plane reflectors traverse along the surface of the plane reflectors according to the robot motion. Nevertheless, when the robot moves in perpendicular direction to the plane reflector surface, the measured reflecting points on it remain at the same point. Consequently, the potential of the proposed system for recognizing the environment was confirmed in this experiment.

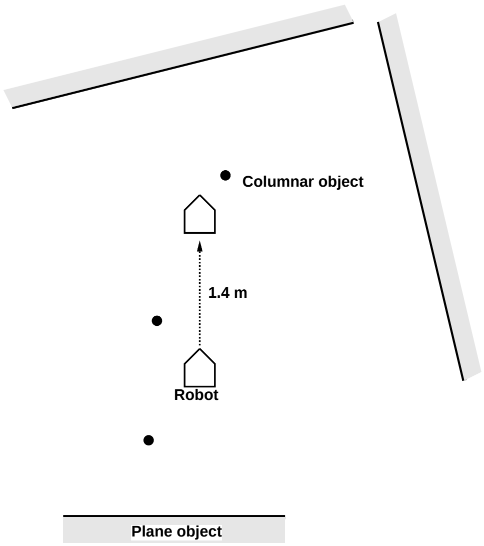

Figure 8: Experimental environment.

5 Conclusion

In this paper, we proposed a new sonar-ring for a mobile robot, which can perform fast and accurate measurements. The proposed system employs simultaneous transmissions/receptions of all directions for fast measurement, and accurate bearing angle measurements by using the difference of time-of-flight. Moreover, the proposed method could achieve an accurate omni-directional measurement in a single transmit/receive cycle, and its potential for recognizing the environment was confirmed in the experiment.

A deficiency of this method is that overlapping of echoes causes hiding of reflecting points which are near by. The size of the hidden area is depending on the directivity of the each receiver and the duration of the echo pulse and it might not be small. This makes it difficult to apply this system to more complicated environment. This is a kind of occlusion problem in ultrasound sensing, and it is required to overcome this occlusion problem for applying this proposed method for a more complicated environment. In the future, after discussing the problem with the prototype system, we would like to design a new electric circuits hardware for real-time measurements.

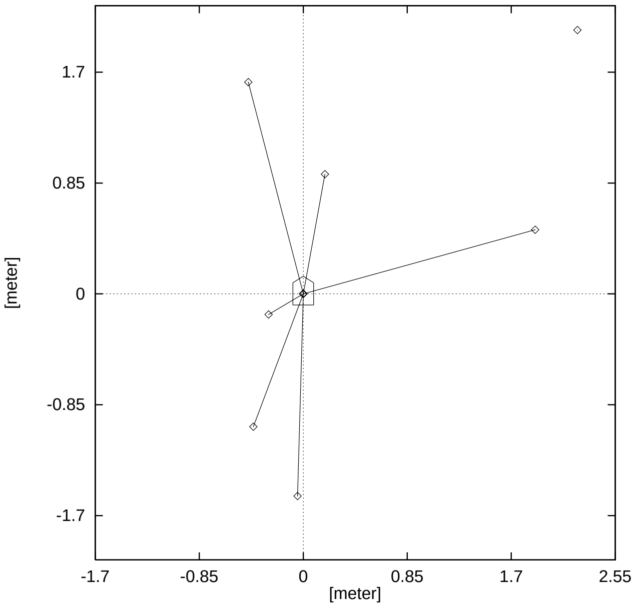

Figure 9: Experimental result in a single measurement. The robot is at the origin of the coordinate axes.

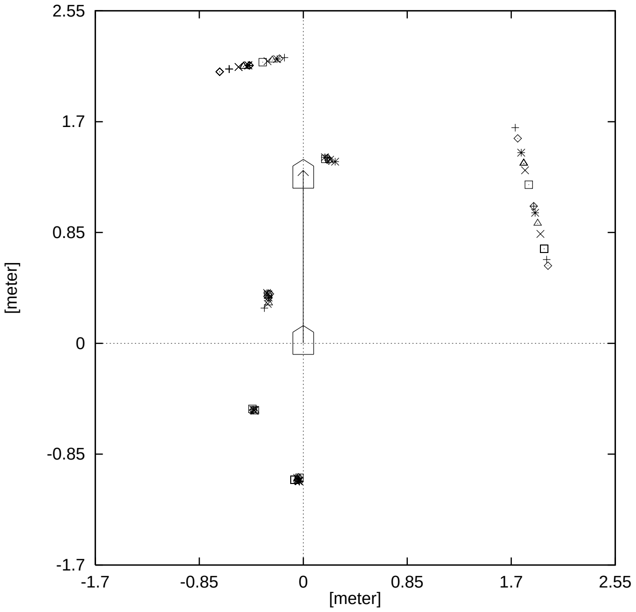

Figure 10: Experimental result. The robot moved along the y-axis starting from the origin of the coordinate axes.

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