COLLISION AVOIDANCE IN A MULTI-ROBOT SYSTEM BY EMULATING HUMAN BEHAVIOUR

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ABSTRACT

This paper proposes a collision avoidance strategy for a multi-robot system, where every robot is considered fully autonomous. The strategy is developed based on a typical human behaviour to avoid a collision while walking. The paper also explores the possibility of using ultrasonic transceivers, fixed on-board every robot as a substitute for vision to determine the position, velocity and direction of motion of another robot. The concept of transformation of inertial frame of reference to determine the position and time of a collision is also suggested. The efficacy of the strategy is demonstrated by means of simulated examples. The simulation program is coded in c++.

Keywords: Collision avoidance, ultrasonic transceiver, inertial frame of reference, path planning, multi-robot system

1. INTRODUCTION

Collision avoidance problems are generally an essential part of robot navigation. The most general classifications of a navigation path very much depends upon whether the environment surrounding a robot is known. Global paths deal with known environments, and hence a path avoiding all the obstacles is selected. However, the challenging task is to work with a local path, where the environment is either completely unknown, or only partially known. This necessitates the use of sensors to detect obstacles, with a collision avoidance strategy to be incorporated into the robot [1].

Collision avoidance and path planning problems, on a majority, deal with only static obstacles. Avoiding moving obstacles is quite a task, with the attendant mathematical calculations that have to be performed on-board. Complications multiply when these moving obstacles are robots with intelligence of their own, which just guarantees that they will not stick to any fixed path. Trapezoidal, logarithmic acceleration or deceleration profiles and multiple kinematic solutions to reach specified points in space complicate motion profiles. A robot now has the added job of determining the velocity of another robot and its direction of motion, keeping track of its motion until a collision is avoided. This calls for a constant monitoring of the entire workspace all around a robot.

One of the ubiquitous position estimation methods using ultrasound [2] is perhaps the most economic and viable solution to this problem. In this paper, apart from using the ultrasound time of flight technique to estimate position, we employ it to determine the direction of motion and the velocity of another robot.

2. UNDERSTANDING HUMAN BEHAVIOUR

The ability to understand human behavior at a fundamental level can have a major impact on the perspective of collision avoidance.

There has been this recent trend of trying to emulate, quite successfully, human traits, or even animals and insects for that matter to impart locomotion to robots. A similar approach to collision avoidance might result in a solution, a lot simpler, robust and easier to comprehend.

The cues are drawn right from the behaviour that is inherent in us, and a behaviour that we so stereotypically implement in our day to day lives to move about, say, in a crowded place. The way we achieve this revolves around three basic actions:

- Persisting with our direction of motion and velocity if there is negligible possibility of an imminent collision.
- Stopping in our path to let the other person persist with his direction and velocity of motion, if a possibility of a collision exists.
- Altering our direction of motion to move ‘around’ the other person, and joining back our original path of motion, with negligible alteration in velocity.

When every robot in the multi-robot system can be made to mimic these basic actions, we can have a reliable collision free robotic workspace.

3. INPUTS TO THE INTELLIGENT CONTROLLERS OF THE ROBOT

A human being uses the help of his vision to judge the position of another human being and the direction in which he is moving. He can obviously neither calculate the velocity of the other human being just by looking at him, nor his own. Then all he needs to do is to compare the other human being's position at every frame of time with respect to his own. In case of an imminent collision, there occurs a certain moment, when distances and positions fall within a particular region close to that point of collision that he can predict to quite a high degree of accuracy that a collision is possible, and eventually take evasive actions.

A robot can use a camera for vision. Then to determine the position, the direction of motion and the velocity of another robot, the first requisite is to capture the other robot in its camera, and for more than one frame. From this data, the on-board processors have to decode the shape and size of the robot. They need to compare multiple frames to determine its direction of motion and velocity, and for all this, we are talking about mathematical calculations that are simply colossal.

In this paper, we explore the possibilities of using an ultrasonic transceiver as a substitute for the camera. The basic principle of operation for sonar ranging is the same no matter what system is being used. The sensing is initiated by first creating a sonic ping at a specific frequency. By determining the time of flight of this ping in its critical path [3], it is possible to determine the direction of motion and the velocity of a robot

Let the maximum range of the ultrasonic sensor be 'r'. The ultrasonic sensor is rotated about its axis at an angular velocity of 'ω' in order to sense object all around the robot. Let 'α' be a small empirical angle through which if the sensor rotates, it is still able to receive a reflected signal, and 'c' be the velocity of sound.

The maximum time interval between the transmitted signal and the received signal is given by:

$$t_m = 2r / c$$

and the angular velocity of the sensor is

$$\omega = (\alpha c) / 2r \qquad \text{Eq. (1)}$$

The distance 'd' between any two robots where 't' is the time interval between the transmitted and received signal is

$$d = ct / 2 \qquad \text{Eq. (2)}$$

The velocity and direction of a robot can be determined by receiving two back-to-back signals that are reflected off from the same robot.

Referring to fig (3.1) let AB and CD represent the paths of two robots R1 and R2 respectively. At a time t1, let R1 emit an ultrasonic signal that is reflected off R2. Using Eq. (3), the distance of separation x1 can be calculated. The direction in which the ultrasonic signal travels from R1 with respect to the direction of motion of R1 is known as $\theta 1$ (measured in counter clockwise direction). Similarly after a very small interval of time δt another signal is transmitted and the distance x2 is determined, with $\theta 2$ known.

Assuming the velocity of R1 is known to itself, the distance traveled by R1 in the time interval between the two signals can be calculated as l1.

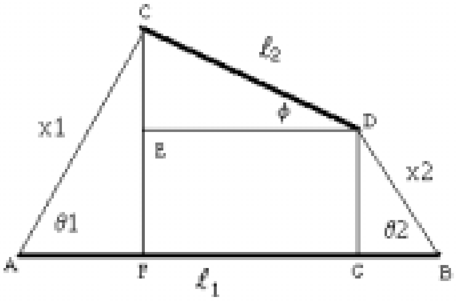


Fig (3.1) [enlarged in scale]

$$ED = l1 - x1 \cos \theta 1 - x2 \cos \theta 2$$
$$CE = x1 \sin \theta 1 - x2 \sin \theta 2$$

$$\phi = \arctan (CE / ED) \qquad \text{Eq. (3)}$$

Hence, the direction of motion of R2 with respect to R1 is determined.

$$l2 = CE / \sin \phi$$

The velocity of R2 can then be calculated as

$$v2 = l2 / \delta t \qquad \text{Eq. (4)}$$

4. POSSIBLE LIMITATIONS OF ULTRASOUND RANGING

The ultrasound technique of estimating distances is not always an accurate method, as speed sound in air is subject to lots of variations, and hence is not constant. This calls for an increase in the number of transceivers to increase the accuracy. A common procedure in this regard is to use an array of ultrasonic transceivers.

Using multiple ultrasonic transceivers, on the other hand, increases the amount of ultrasonic noise in the environment. Another common problem is the scattering produced due to 3-dimensional nature of the other robots.

J. Borenstein et. al. [3] have proposed a solution to reduce erroneous readings due to such noise by means of rapid ultrasonic firing.

Another possible source of error could be the rotation of the ultrasonic transceiver about its axis. This combined with the motion of the robot could lead to certain erroneous readings. Since the velocity of the robot is small, the possibility or error is low. In cases where higher robot velocities might increase this error possibility, an array of transceivers placed all around the robot could be implemented in order to get a 360^0 vision of the environment. The transceivers should ideally be placed every 15^o and hence each robot will have 24 sensors[3]. Such a system tends to be more stable, with an electronic rotation of transceivers proving to be more reliable than a mechanical rotation.

5. TRANSFORMATION OF POINT OF COLLISION BY CHANGE OF INERTIAL FRAME OF REFERENCE

Having calculated the velocity, direction of motion and the distance of separation of R2, R1 has to predict the possibility of a collision if both continue unaltered in their velocities and directions, the point of collision and the time at which it will occur. To do it, it has the following data:

1. Its own velocity v1, and direction of motion with respect to a universal origin O(0,0)
2. The velocity v2 of the robot R2, and its direction of motion with respect to its own path, $\theta 2$.
3. The distance of separation between R1 and R2 at any instant of time, d

The point to be noted here is that the velocities v1 and v2 are with respect to an inertial frame of reference other than these two robots, i.e. these velocities are considered to be measured by an observer who is stationary.

Assuming a collision, to this observer the point of collision will appear to occur at the point C. Since, it is R1 which needs to avoid a collision, we require the point of collision as viewed by an observer on R1. To simulate such an effect, we require transferring the inertial frame of reference to the robot R1, in which case R1 becomes stationary.

The figure traces the paths of R1 and R2 upto the point of collision C as viewed by an observer on an inertial frame of reference other than R1 and R2.

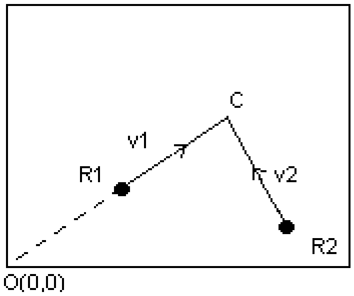


Fig (5.1)

After transferring the inertial frame of reference, where v1=0, v2 is altered to 1v2 (velocity with respect to 1), and R2's direction is changed in such a way that 1v2 is directed towards the stationary R1. This can be demonstrated by simple vector addition, as shown in the figure.

R1 is brought to rest by adding -v1 vector to v1. Hence, the same vector is also added to v2, the resultant of which is 1v2. Consequently, the point of collision is transformed from C to C'.

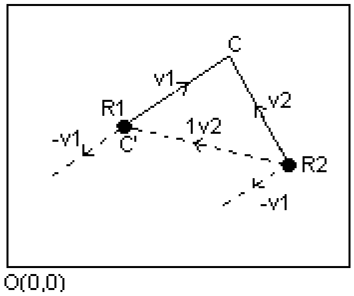


Fig (5.2)

R1 can calculate this relative velocity 1v2 in magnitude and direction. If it finds this vector directed towards, i.e. the point R1 in the figure, then it predicts a collision to occur. Since R1 is aware of the distance d between R1 and R2, the time of collision from that particular instant, t_c can be determined as

$$t_c = d / 1v2 \qquad \text{Eq. (5)}$$

6. ASSUMPTIONS

[A1] All the robots are assumed to travel with uniform velocities.

[A2] The process of deceleration or acceleration either to rest or to a different velocity is assumed to utilize negligible time, or in other words instantaneous.

[A3] The velocities of the robots are considered to be negligible when compared to the speed of sound, and hence all processes involving the ultrasonic transceiver are instantaneous.

7. MARGIN OF SAFETY

We define a parameter, called the margin of safety as the minimum clearance distance between any two robots in order for them to safely avoid a collision.

It is imperative that all the robots in the workspace, at all instances of time are separated at least by the margin of safety in order to render the system safe.

8. COLLISION AVOIDANCE STRATEGY

Keeping in mind the three basic actions resorted to by humans to avoid a collision and the assumptions stated above, the following strategy has been proposed for a fully autonomous multi-robot system.

The strategy is divided into two parts – a set of priorities assigned to each robot, and a set of rules according to which these priorities are opted for.

Note: The strategy is not adhered to by a robot when there is no possibility of a collision, or when the distance of separation of two robots having intersecting paths is greater than the margin of safety.

Each successive step in the strategy is priority based.

Priority 1

A robot continues in its original direction of motion and maintains its velocity unaltered.

Priority 2

Assuming the robot pre-determines the point of collision, the robot decelerates to attain a state of temporary rest at a point that is separated from the point of collision by a 'margin of safety'. It remains in this state for a time that is enough to allow the other robot, by persisting with its direction of motion and velocity, to traverse the margin of safety distance from the point of collision.

Priority 3

The robot attempts to move 'around' the other robot by steering itself to the left. As this move necessitates the robot to rejoin its original path, it is imperative that a right turn or a state of rest follows a left turn, whichever is applicable.

The execution of the priorities is based on the following rules:

1. No two robots to be involved in a collision can execute the same priorities at the same instance, except for priority 3.
2. In event of a possible collision, priority 1 always fails and priority 2 always valid for both the robots, in the first stage of strategy analysis. At a later stage, they can revert back to these priorities.
3. The deciding factor of the first stage is priority 3. This priority fails for a robot that finds itself to the left[1] of the other robot.
4. When two robots have the same paths and directions of motion, priority 3 fails for both.
5. When two robots have the same paths and opposite directions of motion, priority 3 is valid for both.
6. At the end of the first stage, the net priorities valid for both are calculated by each of the robots.
7. In the second stage, the robot that has more priorities to its credit always reverts back to priority 2.
8. The robot having lesser number of valid priorities reverts back to priority 1.

We have in two cases where the net valid priorities add up to the same. They are when two robots have the same path.

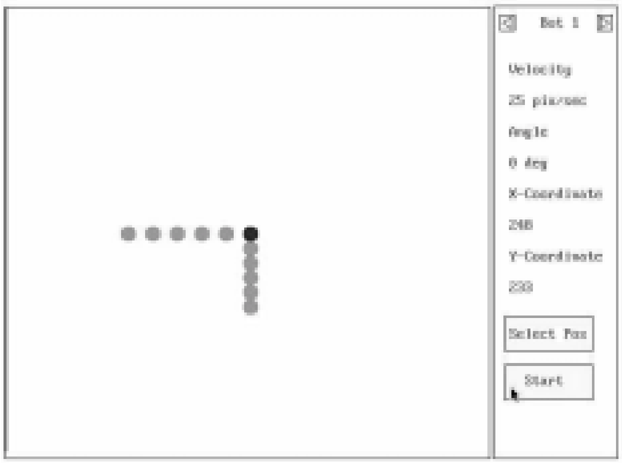
A. When the total adds up to one for both (same direction of motion), the trailing robot (having a faster velocity) acts according to priority 3, whereas the slower robot sticks to priority 1.
B. When the total adds up to 2 in each robot (head-on collision), both the robots opt for priority 3.

9. SIMULATION EXAMPLES

A simulation program coded in c++, where possible scenarios have been conjectured has elucidated the outcome of the collision avoidance strategy. (The screenshots of each situation have been included)

Simulation 1

It is a situation where R1 and R2 are on a path of collision, with R1 to the right of R2.



Velocity
25 pix/sec
Angle
0 deg
X-Coordinate
248
Y-Coordinate
233

Fig (9.1)

As stated earlier, in the first stage priority 1 fails for both while priority 2 remains valid. Hence the deciding factor is priority 3, and in accordance with rule 3, this priority fails for R2 but is valid for R1. Tallying the number of valid priorities for R1 and R2, we find that R1 has two options to avoid a collision, whereas R2 has only one.

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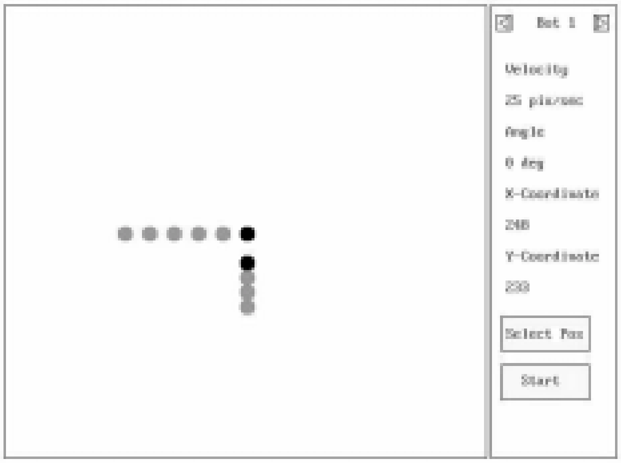
[1] If we assume the sensor to be rotating anti-clockwise about its axis, left of a robot is decided by checking if the angle between the direction of motion, and the shortest path to the other robot (θ1 as in Fig. (3.1)), measured anti-clockwise, is between 0°and 180°

	R1	R2
P1	✗	✗
P2	✓	✓
P3	✓	✗

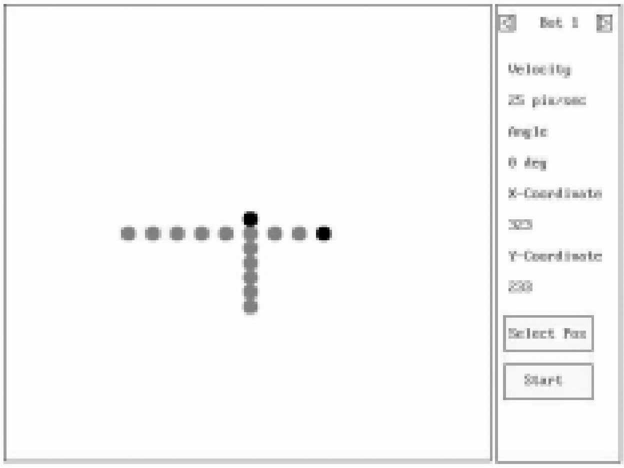
Applying rule 5 and 6, R2 reverts back to priority 1, and R2 opts for priority 2. The outcome is that R2 persists with its initial direction of motion and velocity, while R1 decelerates to a state of temporary rest.



Velocity
25 pix/sec
Angle
0 deg
X-Coordinate
248
Y-Coordinate
233

Fig (9.2)

Fig. (9.2) shows R1 in a state of rest, allowing R2 to pass through the point of collision. The state of rest is attained at a point clear from the point of collision by the margin of safety distance.



Velocity
25 pix/sec
Angle
0 deg
X-Coordinate
323
Y-Coordinate
233

Fig (9.3)

Fig. (9.3) shows R1 continuing with its original direction of motion and velocity, after allowing R2 to travel the margin of safety distance from the point of collision.

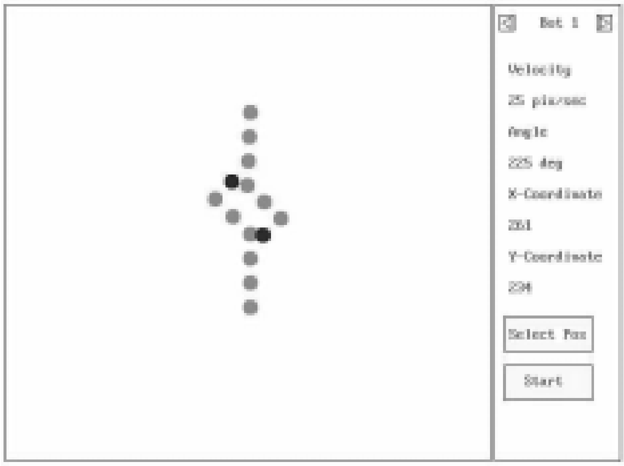
The above outcome simply reverses itself when R1 and R2 swap places.

Simulation 2

This is one of the special cases dealing with a head-on collision. With priorities 1 and 2 remaining the same, we find that priority 3 is also valid for both, which means the net valid priority add up to the same, and equal to two.

	R1	R2
P1	✗	✗
P2	✓	✓
P3	✓	✓

Rule B defines such a case where R1 and R2 opt for priority 3, wherein both the robots turn left, avoid each other and rejoin their tracks. This is simulated in Fig (9.4).



Velocity
25 pix/sec
Angle
225 deg
X-Coordinate
261
Y-Coordinate
234

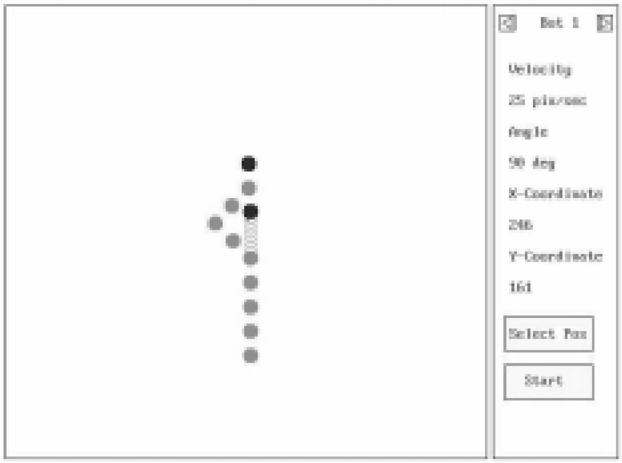
Fig. (9.4)

Simulation 3

This is a situation where R1 and R2 have the same paths and directions of motion. As defined by rule 4, priority 3 is ruled out for both.

	R1	R2
P1	✗	✗
P2	✓	✓
P3	✗	✗

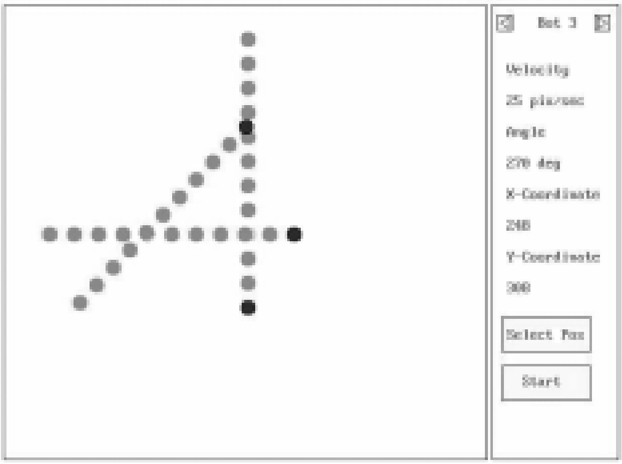
Hence, the net priorities are once again found to be equal to one. As a collision is possible only when the faster robot trails the slower one, the faster R2 uses priority 3 to turn left as a move to overtake the slower R1, which sticks to priority 1 and continues in its same path. This is shown in Fig (9.5)



Velocity
25 pix/sec
Angle
90 deg
X-Coordinate
248
Y-Coordinate
161

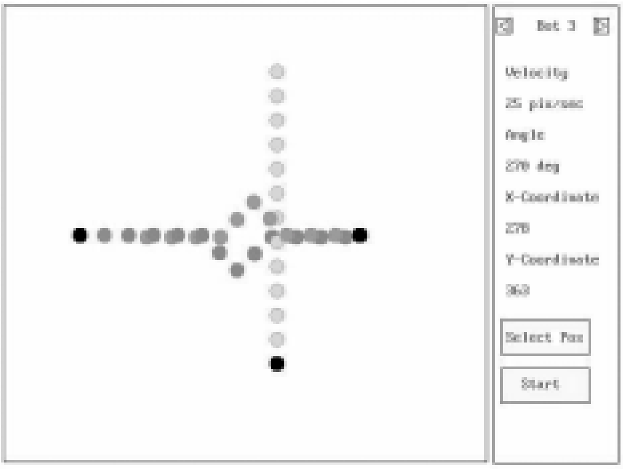
Fig. (9.5)

The strategy has been extended to a workspace of three robots moving in three different directions, in the simulations represented by fig (9.6) and (9.7).



Velocity
25 pix/sec
Angle
270 deg
X-Coordinate
248
Y-Coordinate
308

Fig. (9.6)



Velocity
25 pix/sec
Angle
270 deg
X-Coordinate
278
Y-Coordinate
363

Fig. (9.7)

10. CONCLUSION REMARKS

In this paper, collision avoidance strategy has been proposed for a fully autonomous multi-robot system. The collision avoidance strategy has been framed based on the typical human behaviour to avoid a collision. The robotic system uses ultrasonic transceivers as a substitute to vision to determine the position, direction and velocities of the robots. The use of transformation of inertial frame of reference to obtain the point of collision has been suggested. The paper finally discusses the collision avoidance strategy with respect to a few simulated examples, coded in c++.

11. REFERENCES

[1] Atsushi Fujimori, Peter N. Nikiforuk and Madan M. Gupta, “ Adaptive Navigation of Mobile Robots with Obstacle Avoidance” , IEEE Transactions on Robotics and Automation, Vol. 13, No.4, August 1997.

[2] Hans W. When and Pierre R. Belanger, “Ultrasound-Based Robot Position Estimation”, IEEE Transactions on Robotics and Automation, Vol. 13, No.5, October 1997.

[3] Johann Borenstein and Yoram Koren, “Error Eliminating Rapid Ultrasonic Firing for Mobile Robot Obstacle Avoidance”, IEEE Transactions on Robotics and Automation, Vol. 11, No.1, February 1995, pp 132-138.

[4] R.A. Brooks, “Planning collision-free motions for pick-and-place operations”, International Journal of Robot. Res., Vol.2 No.4, pp19-44, Win, 1983

[5] E.G Gilbert and D.W. Johnson, “Distance functions and their applications to robot path planning in the presence of obstacles”, IEEE J. Robotics and Automation, Vol. RA-1, No.1, March 1985

[6] J. Reif, M. Sharir, “Motion planning in the presence of moving obstacle”, Proc. 26th FOCS, pp 144-154, 1987

[7] Takeshi Tsujimura, “Shape reconstruction using an ultrasonic sensor mounted on a manipulator”, Transactions of ASME Vol. III, 1989