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THE USE OF ULTRASONIC INFORMATION IN PATH CONTROL OF AN INDUSTRIAL ROBOT

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Abstract

Proximity sensing is important to many robotic applications. Seam tracking for arc welding, surface following and guarded motions are a few examples of tasks which can benefit from the use of proximity sensing feedback. This paper exploits the use of ultrasonic sensors, mounted on the last link of a six degrees of freedom manipulator (a Puma 560), with the aim at enabling their use in robotic tasks such as: object detection and localization, surface description and sensor-based path control. For that purpose, it describes approaches for the following processes: 1) evaluation of the transformation which relates a coordinate frame associated to the ultrasonic system and the tool coordinate frame; 2) evaluation of planar surface equations; 3) robotic surface following. At last, the experimental setup in use, which exhibits an hierarchical distributed structure, is described.

Keywords: ultrasonic sensing, surface following, distributed systems

I. Introduction

An improvement on robot flexibility requires an increase on its capability of processing and reasoning about information from its surroundings. In this way, robotics research on areas such as sensory integration and sensor fusion has been receiving an increasing attention. However, a practical implementation and verification of the developed methods is difficult due the limitations on dealing with sensory data of today`s industrial robots. The work described in this paper is integrated in a wider project having in view the development of a robotic system able to support the evaluation of sensorial integration techniques as well as real-time path control strategies [1].

Proximity sensing is important in multiple robotic applications. Among the various sensors which belong to this class there are the ultrasonic sensors, whose application in robotics has been considerable, [2,3,4,5,8], since they are inexpensive, they give range information and also give some insight on surface orientation. This paper, describes geometric modelling aspects related with the use of ultrasonic sensors mounted on the last link of a six degrees of freedom manipulator (Puma 560). It describes approaches for the following processes: 1) evaluation of the coordinate frame associated to the ultrasonic system mounted on the manipulator; 2) evaluation of planar surface equations; 3) geometrical considerations about the surface following task.

I.1Considerations about radiation and reception of sound waves

Analytical expressions for the near and farfield sound pressure and sound intensity produced by a rigid circular piston source, are well known [7]. The sound intensity $i(r,\theta,t)$, at a point $\vec{p}$ in the farfield, as a function of the distance **r**, follows an inverse square law at the points $\theta=0$; for other points, besides that factor of decrease, the intensity still decreases with the increase of the angle θ.

Besides those factors, which describe the behavior of the ultrasonic wave in an homogeneous medium, to analyze the echo picked up by the ultrasonic transducer it is necessary to take into account other factors. Thus, the intensity picked up still depends on the shape of the reflecting surface and on the components responsible for the absorption of the sound either due to the medium (humidity, temperature, dust content of the air, circulating currents, etc.) or due to the own structure of the reflecting surface (texture, etc.). However, considering an homogeneous environment, and considering constant the frequency of the sound wave, it is plausible to evaluate approximated equations relating the orientation angle (angle between the transducer`s line of sight and the normal of the reflecting surface) with the distance r and the echo signal.This kind of information will be useful, as a complement to the distance information, in the application of some of the techniques described in the next sections. In these techniques, the distance d measured by the sensor is always considered the distance from the center of the transducer to the planar surface (distance taken along to the surface normal).

II. Ultrasonic sensor coordinate frame

In this section, an approach to determine the position and orientation of an ultrasonic sensor with respect to the {TOOL} frame is described. The sensor is mechanically attached to the last link of the manipulator. As the sensor measurements are unidimensional, it is enough to relate the measured distances to one coordinate axis, say the z axis of a coordinate frame, which can be assigned to the axis of the ultrasonic beam. The x and y directions can be arbitrarily assigned since that it is taken into account that they form with the z axis an orthonormal coordinate system. Thus, it is only necessary to determine the z axis and the origin point of the sensor coordinate system , say {S}. These two unknowns can be solved separately.The z axis solution can be easily obtained by using the following geometry: the axis of the ultrasonic beam placed normal to a planar surface Π, whose normal is $\vec{n}_{\Pi}=[\pi_1 \quad \pi_2 \quad \pi_3 \quad 0]^T$, which is known with respect to a known coordinate frame, say {BASE} frame. This geometry can be achieved by analyzing the echo signal picked up by the transducer during the operation of positioning. For a given distance, the echo intensity achieves its maximum when the axis of the ultrasonic beam is normal to the surface. For this geometry, the vector $\vec{r}_3$, which represents the z axis of {S} in {TOOL} coordinates, and the normal to the plane $\vec{n}_{\pi}$ are opposite directions, that is,

$$^{BASE}\vec{n}_{\Pi} = -\,^{BASE}T_{TOOL}\begin{bmatrix}\vec{r}_3\\0\end{bmatrix} \qquad (2.1)$$

which gives,

$$\begin{cases}\pi_1 = -(n_x r_{13} + o_x r_{23} + a_x r_{33})\\ \pi_2 = -(n_y r_{13} + o_y r_{23} + a_y r_{33})\\ \pi_3 = -(n_z r_{13} + o_z r_{23} + a_z r_{33})\end{cases} \qquad (2.2)$$

that is, the solution for the z axis of the sensor coordinate frame. In order to obtain the origin of {S} we impose another condition on the above sensor-surface geometry. That is, we assume that a point $\vec{p}$ of the surface is known with respect, say, to the {BASE} frame, and that the transducer is pointing to this point (still normal to the surface). This situation can be achieved, with a certain uncertainty, using a planar object placed over the surface (of course that object should be carefully and experimentally selected). For this geometry, the vector $\vec{p}$ in {S} coordinates, is given by

$$^{S}\vec{p} = [0 \quad 0 \quad d \quad 1]^{T},$$

where d is the distance measured by the sensor. Thus, the vector $\vec{p}$ can be expressed in {BASE} coordinates as,

$$^{BASE}\vec{p} = {}^{BASE}T_{TOOL}\ {}^{TOOL}T_{S}\ {}^{S}\vec{p}$$

$$= \begin{bmatrix} \vec{n} & \vec{o} & \vec{a} & \vec{t} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \vec{r}_1 & \vec{r}_2 & \vec{r}_3 & \vec{l} \\ 0 & 0 & 0 & 1 \end{bmatrix} {}^{S}\vec{p} \qquad (2.3)$$

that yields the following set of equations,

$$\begin{cases} x = (n_x r_{13} + o_x r_{23} + a_x r_{33})d + n_x l_x + o_x l_y + a_x l_z + t_x \\ y = (n_y r_{13} + o_y r_{23} + a_y r_{33})d + n_y l_x + o_y l_y + a_y l_z + t_y \\ z = (n_z r_{13} + o_z r_{23} + a_z r_{33})d + n_z l_x + o_z l_y + a_z l_z + t_z \end{cases} \qquad (2.4)$$

where the only unknowns are the elements of the vector $\vec{l}$ which represents the origin of {S} with respect to the {TOOL} frame. As we mentioned, there is an uncertainty associated with the normal and the point $\vec{p}$ of the plane (due both processes of determination and of calibration). A possible way to minimize that uncertainty, may be by using several known points of different planes. In this case, it is possible to apply a least-squares estimation: 1) in the evaluation of the orientation of the frame by using several planes; 2) and, in the evaluation of the origin by using several points.

III. Evaluation of planar surface equations by using ultrasonic sensors

The solution for a planar surface, that follows, consists on the evaluation of three points of the surface obtained by positioning the ultrasonic sensor at three different spatial positions (stations). For that positioning the manipulator is used, and the following conditions are assumed: 1) the transducer is mounted on the last link of the manipulator; 2) the transformation which relates the sensor position and orientation to the {TOOL} frame is known.The sensor frame {S}, should maintain the same orientation with respect to the {BASE} coordinate frame for the three spatial positions. Under this condition, the angle θ, angle between the surface normal and the axis of the ultrasonic beam, will maintain a constant value for the different sensor positions. Following this strategy, on one hand, we obtain a simplicity on the specification of the trajectory with the guaranty that the condition θ<θc yields (being θc the critical angle value, from which there is no echo reception). On the other hand, there is uniformity on the distances measured, given the constancy of the θ value. Considering that the measurements are taken under the described geometry, the points $\vec{p}_i$ (i=1,2,3), of the surface with respect to the {S} frame, are expressed by

$$^{S}\vec{p}_i = \left[0 \quad 0 \quad \frac{d_i}{\cos\theta} \quad 1\right]^{T} \qquad (3.1)$$

where, d_i (i=1,2,3) represents the distance measured by the sensor at the station i and θ represents the angle between the surface normal and the direction defined by the axis of the ultrasonic beam.

Applying the transformation $^{BASE}T_{ST_i} = \left(^{BASE}T_{TOOL}\right)_i\ ^{TOOL}T_S$ to the equation (3.1) yields,

$$^{BASE}\vec{p}_i = \begin{bmatrix} (n_{xi} r_{13} + o_{xi} r_{23} + a_{xi} r_{33})\frac{d_i}{\cos\theta} + n_{xi} l_x + o_{xi} l_y + a_{xi} l_z + t_{xi} \\ (n_{yi} r_{13} + o_{yi} r_{23} + a_{yi} r_{33})\frac{d_i}{\cos\theta} + n_{yi} l_x + o_{yi} l_y + a_{yi} l_z + t_{yi} \\ (n_{zi} r_{13} + o_{zi} r_{23} + a_{zi} r_{33})\frac{d_i}{\cos\theta} + n_{zi} l_x + o_{zi} l_y + a_{zi} l_z + t_{zi} \\ 1 \end{bmatrix} \qquad (3.2)$$

In case there is one estimation for the angle θ, the set of equations (3.2) (with i=1,2,3) gives us the necessary data to establish the equation of the planar surface Π [9] given by

$$\pi_1 x + \pi_2 y + \pi_3 z + \pi_4 s = 0 \ . \qquad (3.3)$$

In some particular conditions it may be possible to estimate values for the angle θ (for an homogeneous environment, provided that the planar surface dimensions and the position of the transducer relatively to the surface is such that the totality of the emission cone intercepts the surface, and there is no place to interferences on the sound wave due to any object). However, for the majority of the cases those conditions do not verify. In view of that, the solution is too particular and it is necessary to exploit alternative solutions where a no dependency in relation to θ must be a goal.

A solution of this type is obtained by imposing a new restriction on the trajectory, to be followed by the manipulator, in order to position the ultrasonic sensor at the three stations. In the previous solution, the stations were allowed to define parallel planes whose normal was defined by the z direction of the frame {S}. In the new solution the stations are constrained to be placed only on one of any of those planes. For these conditions, it is possible to define a frame, say {U}, as illustrated in the Figure 3.1, such that its origin coincide with the station 1 origin, the station 2 lies on the x axis, the station 3 lies somewhere on the x-y plane, and the direction of the z axis of {U} coincides with the direction of the z axis of the three stations.

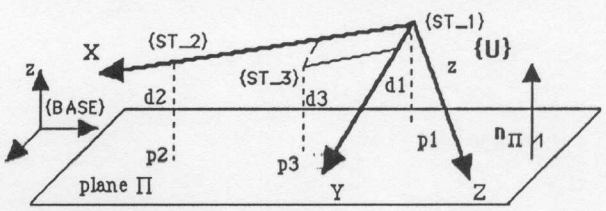

Fig.3.1 Geometry of the coordinate system {U}.

Given this geometry, the vector $\vec{p}_1$ with respect to the {U} coordinate frame is known [2,3],

$$\vec{p}_1 = \left[\frac{d_1(d_1 - d_2)}{S_{2x}} \quad \frac{d_1(d_1 - d_3)}{S_{3y}} - \frac{S_{3x} d_1(d_1 - d_2)}{S_{2x} S_{3y}} \quad \sqrt{d_1^2 - p_{1x}^2 - p_{1y}^2}\right]^{T} \qquad (3.4)$$

where S2x,S3x and S3y, p1x and p1y represent, respectively, the x coordinate of the origin of the station 2, the x and y coordinates of the origin of station 3 and the x and y components of the vector $\vec{p}_1$. With $\vec{p}_1$ known it is straightforward to establish the equation for the plane Π with respect to the coordinate frame {U},

$$^{U}\Pi = [\pi_1 \quad \pi_2 \quad \pi_3 \quad \pi_4] \qquad \text{with} \quad \begin{cases} \pi_1 = n_{\Pi x} \\ \pi_2 = n_{\Pi y} \\ \pi_3 = n_{\Pi z} \\ \pi_4 = \|\vec{p}_1\| \end{cases} \qquad (3.5)$$

whose normal is $\vec{n}_\Pi = -\frac{\vec{p}_1}{\|\vec{p}_1\|} = -\frac{\vec{p}_1}{d_1}$ (3.6)

The solution for the vector $\vec{p}_1$, and thus for the plane, is still more compact in the case of the station 3 lies on the y axis of the frame {U}, as we can conclude from the equation (3.4) (equalizing S3x to zero).

By using simultaneously three sensors, placed according to a geometry that defines a frame {U}, the planar surface equation is obtained in only one station. This sensor arrangement will still allow the exploitation of control strategies for path control. This is possible by exploiting the fact that this sensor system gives us enough information to reorient the X-Y plane of {U} to become parallel with the planar surface, to be followed. Besides, with all sensors oriented normal to the plane, the plane equation can be estimated by reading only one sensor.

IV. Geometric considerations about the surface following task

Let {U} be the coordinate system associated to a three sensor system, as defined in the previous section. The x-y plane of {U} is parallel with the planar surface Π when all the sensor measurements are equal. Thus, from the equation (3.4), this situation yields,

$$\vec{p}_1 = [0 \quad 0 \quad d_1]^T \tag{4.1}$$

This state may be accomplished by doing two rotations in order to cancel the p_{1x} and p_{1y} components. From the Figure 4.1 and Figure 4.2, it can be written the following equations for the p_{1x} and p_{1y} components,

$$\begin{cases} p_{1x} = d_1 \sin\phi_1 \\ p_{1y} = d_1 \sin\phi_2 \\ \text{where } d_1 = \|\vec{p}_1\| \end{cases} \tag{4.2}$$

where: 1) ϕ_1 is the angle between the z axis and the $\vec{p}_1$ vector after being rotated around the x axis onto the Z-X plane; 2) ϕ_2 is the angle between the z axis and the $\vec{p}_1$ vector after being rotated around the y axis onto the Z-Y plane. Another possible analysis for p_{1x} and p_{1y} may be done by rotating the $\vec{p}_1$ vector onto the X-Y plane (see Figure 4.2) as follows: 1) by rotating around the x axis, which gives the p_{1x} component; 2) by rotating around the y axis, which gives the p_{1y} component. The angle ϕ_3 in the Figure 4.2 is related with the p_{1z} component. From the equations (3.4) and (4.2), we obtain the following equations for ϕ_1 and ϕ_2

$$\begin{cases} \sin\phi_1 = \dfrac{d_1 - d_2}{S_{2x}} \\ \sin\phi_2 = \dfrac{1}{S_{3y}}\left((d_1 - d_3) - \dfrac{S_{3x}}{S_{2x}}(d_1 - d_2)\right) \end{cases} \tag{4.3}$$

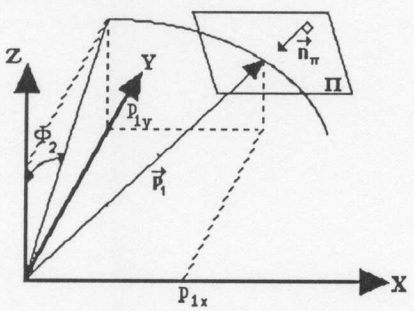

Fig. 4.1 Illustration of the angle ϕ_2

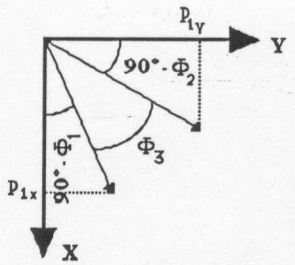

Fig. 4.2 Illustration of the angles ϕ_1, ϕ_2 and ϕ_3

As Wampler [10] pointed out, and as it can be concluded from the above considerations, the surface following task may be accomplished by controlling three degrees of freedom of the task space. If we consider a velocity control, thus the task is accomplished by controlling the angular velocities about the x and y axis and the linear velocity along the z axis, in our case, with respect to the {U} frame. The remaining three degrees of freedom are left to be freely program specified.

If a velocity control is chosen, a damping control scheme [11] can be applied. To implement the damping control, we must find out the 6x6 **K** matrix coefficients, which should be selected taking into account:

1) task constraints;
2) dynamics constraint.

As regards the item 1), for the surface following task, the selection criteria is accomplished by using the above geometrical results. That is, the X-Y plane of {U} become parallel with the plane Π by accomplish the following two rotations:

1) a rotation about the y axis, $\Delta\phi_y = -\phi_1$ (4.4)

2) a rotation about the x axis, $\Delta\phi_x = -\phi_2$ (4.5)

Finally, to position the x-y plane at a distance d_d above the planar surface it should be performed a translation Δx_z,

3) $\Delta x_z = -(d_d - d_1)$ (4.6)

along the z direction of the {U} coordinate system. Thus, we may define a correction velocity vector, as

$$\Delta\dot{X} = \mathbf{K}\,\Delta X = [0 \quad 0 \quad k_{33}\Delta x_z \quad k_{44}\Delta\phi_x \quad k_{55}\Delta\phi_y \quad 0]^T \tag{4.7}$$

where

$$\Delta X = [0 \quad 0 \quad \Delta x_z \quad \Delta\phi_x \quad \Delta\phi_y \quad 0]^T \tag{4.8}$$

is the position error vector.

To select the three K gains, which must guaranty the system stability, it must be analyzed the real-time behavior of the system. For that purpose, we follow a similar system model and discrete analysis as that described by Wampler [10], where the dynamic behavior of the manipulator and the serial processing are modeled by a set of difference equations.

V. Experimental setup

The experimental setup is based on an integrated and evolutive system, in which the addition of new sensors and actuators is possible in a modular fashion. The control system exhibits an hierarchical structure following a distributed processing model [1], as illustrated in the Figure 5.1. To establish the communications between the Supervisor system (a 16MHz, 32-bit, and 80386 CPU personal computer) and the distributed slave systems, a serial network in a bus topology, the Bitbus [6], is used. This network exhibits a good performance in handling short messages allowing high order rates of information transmission, (up to 2.4 Mb/s in half-duplex synchronous mode).

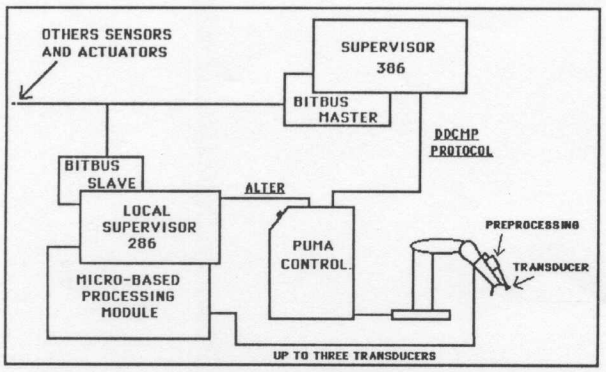

Fig.5.1 Experimental setup

The connections to the Puma controller, the supervisory and the real-time path control communications, are assured by two software modules. The supervisory communication which use the digital-data-communications-message-protocol (DDCMP) is assured by the Supervisor system while the real-time connection is performed by an 8031-based board (with multitasking capabilities), plugged on the Local-Supervisor. The Local Supervisor, a 16-bit personal computer (CPU 80286 and FPU 80287), carries out the important role of allowing the implementation and evaluation of sensor-based closed-loop control strategies.

A set of boards, corresponding to a variety of functions at the sensor and actuator level, has been implemented in our laboratory for this distributed control system being the ultrasonic processing modules one of them. Each of the three ultrasonic sensors used has an ultrasonic ranging module with a single transmitter and receiver transducer. The transducers have a resonant frequency of about 215KHz and the ranging modules output two signals: a digital signal whose width is directly proportional to the distance and an amplified analog echo signal. The processing of these signals is carried out by two physically separated modules. A remote preprocessing module, one per each transducer, which is placed on the manipulator close to the transducer, as illustrated in the Figure 5.2. Additionally, a PCAT-bus microcontroller-based module with the capacity of processing in simultaneous information from three remote modules is used.

The repetition rate of the trigger pulse applied to the ultrasonic ranging module, which controls the sound emissions, is programmable and can assume discrete values between 61Hz and 400Hz. This capability allows for variable triggering as a function of the distance to be measured. This is of great importance when real-time performance is required. The analog signal is rectified and converted to digital, using a 12-bit ADC with serial output. At the micro-based board this signal is converted to parallel and stored in a FIFO memory. These memories enable the parallel processing up to three analog signals (from three different transducers) and allow high sampling rates. The complete process of analog-to-digital-to-serial-to-parallel is performed in 5 μsec. The pulse width is measured with 12-bit resolution by an interval counter also at the AT-bus processing board.

As we have already mentioned the robotic system exhibits a distributed processing model. The software structure of the overall distributed system is composed by several protocolar and functional layers: 1) a data link layer which implements a subset of the synchronous-data-link-control-protocol (SDLC); 2) a transaction layer which defines a message format that ensures the transparency in the exchange of information between the master and the slave tasks; 3) an application support layer which implements several interface procedures between the user programmes and the action procedures distributed throughout the robotic system; 4) the application layer which corresponds to the user applications. This layer includes utilities software such as: development tools; software for files transfer and software to configure the robotic system.

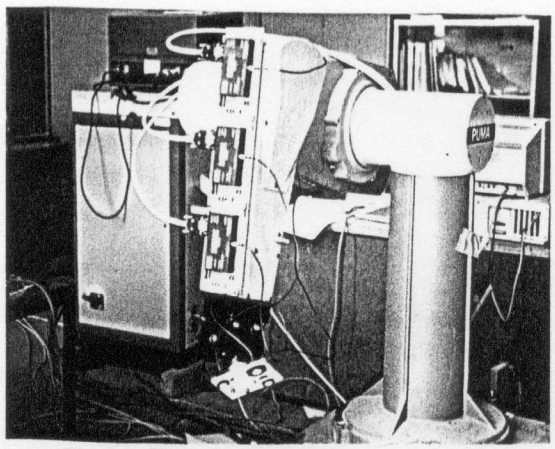

Fig.5.2 Ultrasonic system mounted on the Puma

VI. Conclusions

In this paper it was described some methodologies with the aim to obtain three dimensional information of planar surfaces using ultrasonic sensors attached to the end-effector of a six degrees of freedom manipulator. Thus, it was described an approach to determine the geometrical transformation between the referential associated to the sensor system and the referential of the last link of the manipulator as well as an approach to evaluate planar-surface equations using the ultrasonic system. In another section, some geometrical aspects related with the surface following task were presented. At last, the experimental setup in use was addressed. This work represents an initial stage of a wider project, having in view the use and integration of sensing data from a variety of sources for robotics tasks, such as: sensor-based path control and environmental map construction. In parallel with the work on the implementation of the communication structure of the distributed system, more sensors are going to be added to the system such as: proximity sensors (pair of laser diode - position sensing device (PSD) and pairs of light emitting diodes - photodiodes) and a wrist sensor to investigate motion on contact.

VII. References

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