論 文

An Automatic Engagement Robot System Using Combined Acoustic and Visual Sensors

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결합된 음향 및 시각 센서를 사용한 자동 인게즈먼트 로보트 시스템

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ABSTRACT

A material handling robot system designed for loading and unloading of a plannar object on a pallet in unstructured field environment is presented. The proposed system uses combined acoustic and visual sensing data to determine the specific locations of the two slots of the pallet, so that the forklift can move close to the slot and engage it for transport.

In this paper, to reduce the complexity of the material handling system, we have developed a method based on the integration of 3-D range data from Poraloid acoustic sensor along with 2-D visual data obtained from an CCD camera. Data obtained from the two separate sources complements each other and is used in an efficient algorithm to control this material handling robot system. A camera at first is used based on the concept of far-away vision to determine areas of linear scanning of acoustic sensors. As near vision, range map is obtained from linear scanning and is applied to determine the position and orientation of a pallet using least mean square method based on the concept of near vision. Once the position and orientation of the pallet is determined, 2-D visual data is used to determine the engagement location of a pallet by using edge detection and Hough transform techniques. The system developed is evaluated through the hardware and software implementation. The experimental results are presented.

要 約

비 구조적인 주변 환경에서 평면 팔레트(planar pallet)를 포크리프트(forklift)로 적재하거나 하역하기 위한 물류용 재료운송 로보트 시스템을 제안한다. 제안한 시스템은 음향(acoustic)센서와 시각(visual) 센싱데이타를 사용하여 팔레트에 지정된 2개의 스롯(slot)의 위치를 결정하고 포크리프트를 팔레트의 스롯에 인게즈(engage)한다.

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본 연구에서는 재료운송 시스템의 복잡성을 줄이기 위해서 폴라로이드(Poraloid) 음향센서의 3차원 거리 데이타와 CCD 카메라에서 얻은 2차원 시각 데이타를 통합하는 방법을 개발한다. 2개의 다른 소스로부터 얻은 데이타는 서로의 미비점을 보안하며 재료운송 로보트 시스템을 제어하기 위한 효율적인 알고리즘을 제공한다. 카메라는 far-away vision 개념에 의한 음향센서의 선형 스캐닝(scanning) 대역을 우선 결정한다. 선형 스캐닝에 의하여 얻어지는 거리 데이타(Range Map)는 least mean square방법을 사용하여 팔레트의 위치와 자세(position and orientation)를 결정한다(near vision). 팔레트에 대한 위치와 자세가 결정되면 다시 시각센서를 이용하여(close vision) 에지(edge)탐지와 Hough transform 기술을 적용하여 팔레트에 대한 포크리프트의 인게지먼트 위치를 구한다. 개발된 시스템은 하드웨어와 소프트웨어로 구현하고 평가하며 실험적인 결과도 제시한다.

Ⅰ. Introduction

Typical tasks for a sensor based robotic system is usually to locate, recognize and transport a target object, to load and unload a cargo, to place items into stock, and to release or off-load the palletized cargo from line haul vehicles in assembly line. The robotic system is very useful in the field of automation. It is also very applicable to nuclearly, biologically, and chemically(NCB) hazardous environments in addition to a normal outdoor condition; adverse lighting, temperature, or precipitation.

Currently, lots of robotic systems employ verious type of sensory systems to augment the intelligence of the robot systems. Visual sensors are usually used to provide the environmental information around the robotic system. However, a typical robotic system whose main sensor is an optical camera requires known patterns within field environment. It is inevitable to reduce prohibitive amounts of processing time for the real time applications.[7] With such a system, difficulties can arise when system cannot detect known patterns due to the adverse environment conditions.

In this paper, a system equipped with an acoustic sensor is presented to solve the inherent problems of an optical camera in terms of processing time and illumination.[1,3,6,8,9] However, the acoustic sensing system has its own problems. The acoustic signal beam spread allows echoes to be obtained from more than one reflection source. But since a pallet usually has the large planar surfaces, the echo problems of the acoustic ranging system can be eliminated by adopting proper techniques. It is obviously desirable to design a system through the combination of more than one sensor data in such a way that increase system flexibility with improved reliability, accurancy, and speed. We have developed a material handling robot system through the combination of acoustic and visual sensing. We assume that objects are packed in a planar wooden box. The wooden box is right on the pallet specially designed for forklifting. For the convenience, we call an object on the pallet simply by a pallet.

A brief description of the overall system configuration is presented in section Ⅱ. Section Ⅲ describes the distance measurement process of acoustic sensor. The procedure for computing the position and orientation of a pallet is discussed in section Ⅳ. We use range data obtained from linear scannings of an acoustic sensor. Once the position and orientation of a pallet is estimated, the engagement, which spots to hold and how to approach it, should be determined. The determination of the engagment points of the planar surface of the pallet is presented in section Ⅴ. The experimental results are included in section Ⅵ. The conclusions are described in section Ⅶ.

Ⅱ. Overall system configuration

The overall system configuration of the sensor-based robotic system used in the experiments is shown in Fig. 1. The major components include a

PUMA 560 robot, a real time image processor, Poraloid acoustic sensor, a wooden pallet and Work Station. The working prototype of the end-effector, multi-sensor based forklift, is shown in Fig. 2 to guide the robot and to perform the engagement tasks.

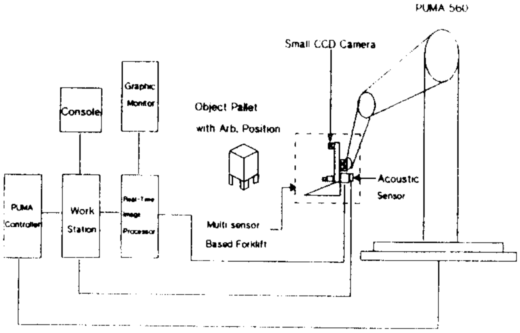


Fig. 1. Overall system configuration

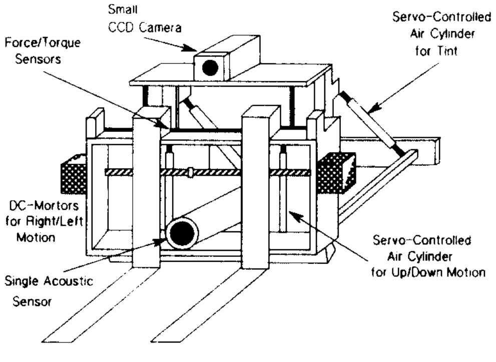


Fig. 2. Model of multi-sensor forklift system

We propose to acquire sensory information hierarchically based on three distinct phases: "far-away", "near", "close-to". During the far-away sensing phase, an optical camera system works to acquire global information about a scene far away.

If the specific local information, e.g. a pallet, is found to be useful for the performance of the task based on a prior knowledge of the environmental database, forklift will move to a pallet and enter into the second phase. To be brief, the camera used in this phase provides the 3-D spatial information for the area to be scanned by an acoustic sensor which will be discussed hereafter.

In the near sensing phase, the accuracy of object measurements can be increased by using closer point of view. If we are close to the pallet, we may no longer be able to see all of the object in one view. However, we can still measure its positioning information with increased accuracy. We can then fine-tune this information based on the initial estimation obtained from the far away phase. An acoustic sensory system is used for this phase to·estimate the orientation of a pallet. If the information acquired is found to be interest in the performance of the task based on the a prior knowledge, we proceed to the next phase.

In the close-to phase, quite obviously, several sensors are no longer useful and thus are no longer queried for information. The visual camera system is again introduced to produce the information for the engagement of a forklift.

Ⅲ. Acoustic transducer and ranging system

In acoustic ranging, a sinusoidal electrical pulse excites a piezoelectric transducer which, in turn, generates and transmits an acoustic pulse, through air, toward the target object (i.e. pallet). A fraction of the incident acoustic energy is reflected back to the transducer and detected. The time delay between the pulse transmission and the first echo detection is multiplied by one-half the acoustic speed of the pulse to compute distance between the sensor and the object. Therefore, spatial distance from the object and the transducer is given by Eq. (1).[5]

$$r = C \cdot \frac{T_r}{2} \tag{1}$$

where r is distance. C is sound velocity. T_r is the time when amplitude of the echo first reaches to a prefixed threshold level. Polaroid acoustic ranging sensor was used in our experiment.

Ⅳ. Determination of the orientation by the acoustic range data

In general, the object has the three position and three orientation parameters that specify the object position and orientation relative to a fixed reference frame. We have chosen a convention to denote the object orientation using the pan, tilt, and swing angles. The pan, tilt, and swing angles of the object are denoted by θ, φ and ϕ respectively. The rotated reference frame is then obtained from the original reference frame by a rotation of θ angle about the oz axis followed by a roation of φ angle about the ox axis in the reference frame and finally a rotation of ϕ angle about the oy axis in the reference frame.

Let us start with the relatively simple problem of finding the pan angle of the planar surface of pallet, i.e., we assume the pallet is placed on the horizontal surface. φ and ϕ are zeros respectively. As shown in Fig. 3, the reference frame is the xyz coordinate and the $x'y'$ axes is the xy axes rotated by an angle of θ about the oz axis. Let the planar surface of a pallet be on the $z'x'$ plane. The acoustic sensor is arranged at a point s_1 on the xy plane and radiates down in a direction of the line parallel to the y axis. The orientation of the planar surface can be determined by translating acoustic sensor a point s_2 on a line parallel to the x axis through s_1 as shown in Fig. 3. Two sampling points, s_1 and s_2 of acoustic sensor are represented by $s_1=[x_0\ y_0\ 0]$ and $s_2=[-x_0\ y_0\ 0]$ with respect to the xyz reference frame. Let the range magnitudes be r_1 and r_2 respectively.

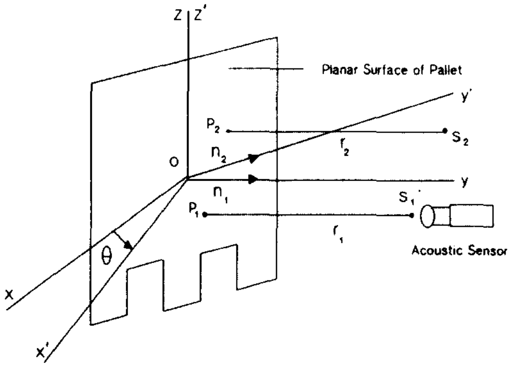


Fig. 3. Determination of the pan angle of the planar surface of a pallet

A unit vector, n_1 normal to the zx plane from the xyz reference frame is given by Eq. (2).

$$n_1=[0\,1\,0] \tag{2}$$

The normal vector of the planar surface which is obtained by rotating the vector n_1 about the z axis by θ is given by Eq. (3).

$$\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} \tag{3}$$

Let n_2 be expressed by $n_2=[-\sin\theta\ \cos\theta\ 0]$. The planar surface can be expressed by Eq. (4).

$$[x\,y\,z]\cdot \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} = 0 \tag{4}$$

Let the signal reflection points on the planar surface of a pallet from the acoustic sensor at s_1 and s_2 be p_1 and p_2 respectively. The locations of p_1 and p_2 are given by Eq. (5).

$$p_1=[x_0\ \ x_0\tan\theta\ \ 0],\quad [-x_0\ \ -x_0\tan\theta\ \ 0] \tag{5}$$

The problems of finding orientation of a planar surface can be simplified by recognizing the $x'y'$ plane as shown in Fig. 4. A right triangle can be formed by drawing two lines parallel to the y axis through p_1 and p_2. The pan angle θ of the planar surface is given by Eq. (6).

$$\tan\theta=\frac{(r_2-r_1)}{D_1} \tag{6}$$

where D_1 is sampling distance between the two consecutive sampling points along the line parallel to the x axis.

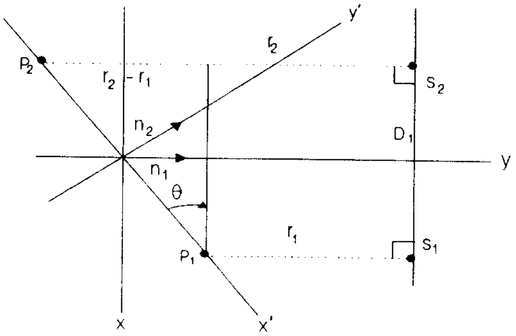


Fig. 4. Geometry of a simplified 2-D pan angle determination

Fig. 5 illustrates a more complex example for determining the pan and tilt angles simultaneously assuming that the pallet has two degree of freedom. An acoustic sensor lies at a point, s_1 on the xy plane and radiates down to a direction of the line parallel to the y axis. This acoustic sensor is translated horizontally to the next sampling point, s_2 for measuring the pan angle and then translated vertically to the third sampling point, s_3 for measuring the tilt angle. The location of the three points are $s_1=[x_0\ y_0\ 0]$, $s_2=[-x_0\ y_0\ 0]$, and $s_3=[x_0\ y_0\ z_0]$ with range magnitudes r_1, r_2, and r_3 respectively with respect to the xyz reference frame.

The unit vector, n_1 normal to the zx plane from the xyz reference frame is given by $n_1=[0\ 1\ 0]$. The unit vector, n_2 normal to the $z'x'$ plane is given by Eq. (7)

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi & -\sin\varphi \\ 0 & \sin\varphi & \cos\varphi \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} -\sin\theta \\ \cos\theta\ \cos\varphi \\ \cos\theta\ \sin\varphi \end{bmatrix} \tag{7}$$

n_2 can be represented by $n_2=[-\sin\theta\ \cos\theta\ \cos\varphi\ \cos\theta\ \sin\varphi]$. Thus, the planar surface can be expressed by Eq. (8).

$$[x\ y\ z] \cdot \begin{bmatrix} -\sin\theta \\ \cos\theta\ \cos\varphi \\ \cos\theta\ \sin\varphi \end{bmatrix} = 0 \tag{8}$$

Let the signal reflection points on the planar surface from acoustic sensor s_1, s_2, and s_3 be p_1, p_2, and p_3 respectively. Using Eq. (8), the locations of p_1, p_2, and p_3 can be given by

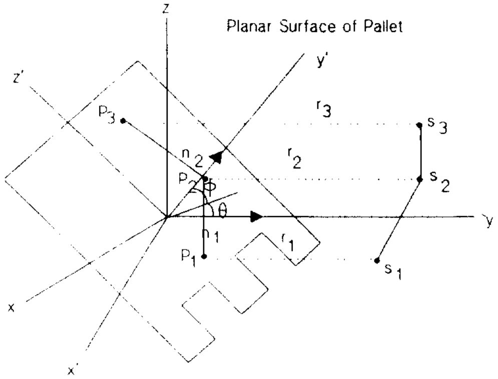


Fig. 5. Determination of the pan and tilt angles of the planar surface of a pallet

$$p_1=[p_{x1}\ p_{y1}\ p_{z1}],\quad p_2=[p_{x2}\ p_{y2}\ p_{z2}],\quad p_3=[p_{x3}\ p_{y3}\ p_{z3}] \tag{9}$$

where $p_{x1}=x_0$, $p_{y1}=x_0\sin\theta/\cos\theta$, $p_{z1}=p_{z2}=0$, $p_{x2}=-x_0$, $p_{y2}=-x_0\sin\theta/\cos\theta$, $p_{y3}=-(x_0\sin\theta\cos\varphi+z_0\sin\varphi)/(\cos\theta\cos\varphi)$, and $p_{z3}=z_0$.

Using the components of p_1, p_2, and p_3, the slopes of the lines passing through p_1 and p_2 and through p_2 and p_3 can be obtained as follows.

$$k_1=\frac{p_{y2}-p_{y1}}{p_{x2}-p_{x1}}=\frac{\tan\theta}{\cos\varphi} \tag{10}$$

$$k_2=\frac{p_{y3}-p_{y2}}{p_{z3}-p_{z2}}=-\frac{\sin\theta}{\cos\varphi} \tag{11}$$

where k_1 is the slope of the line passing through p_1 and p_2. k_2 is the slope of the line passing through p_2 and p_3. Thus, the pan and tilt angles can be solved by the equations (10) and (11).

The acoustic ranging system suffers from random interference and random noise. The sensor may have the electronic timing errors and acoustic amplitude fluctuations. Other sources of noise are changes in medium properties that affect the velocity of sound, such as air temperature, gaseous composition, etc. These are the sources of the range error. In order to perform the task precisely it is necessary to reduce the data error of the range magnitudes. The error can be decreased by increasing the number of measurements along linear scanning paths as shown in Fig. 6.

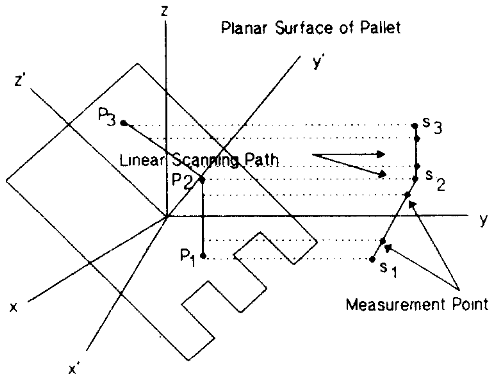


Fig. 6. Linear scanning of acoustic sensor

If there are no errors of range data, the range data from the linear scanning along the line parallel to the x axis through s_1 and s_2 should lie on a line. This line equation can be described by Eq. (12).

$$r = a + KT \tag{12}$$

where r is the range magnitude at each sampling point. a is a value on an axis intersected with the line slope of range magnitudes. K is the slope of the line of range data. T is sampling time.

Since the system is subject to the errors, linear equation, Eq. (12) is not satisfied exactly by the range magnitudes of r and T.[4] If we denote the range data of r measured at a time $T = T_i$ by r_i, the range magnitude, r_i lies randomly approximated on a straight line due to the inherent range error. The relation between r_i and T_i can be written as Eq. (13).

$$r_i = a + KT_i + e_i \tag{13}$$

where e_i represents an inherent range error resulting from acoustic ranging system. For simplicity purpose, it is convenient to express the following analysis in matrix notation, Eq. (13) can be rewritten as Eq. (14).

$$R = AX + E \tag{14}$$

$$R = \begin{bmatrix} r_1 \\ \vdots \\ r_m \end{bmatrix}, \quad A = \begin{bmatrix} 1 & T_1 \\ \vdots & \vdots \\ 1 & T_m \end{bmatrix}, \quad X = \begin{bmatrix} a \\ \\ K \end{bmatrix}, \quad E = \begin{bmatrix} e_1 \\ \vdots \\ e_m \end{bmatrix}$$

where m is the number of the measurements.

The error vector is $E = R - AX$. The criterion we use to find the best straight line is that we minimize the sum of squares of the errors of the range data. The solution for the least squares is

$$X = (A^T A)^{-1} A^T R \tag{15}$$

Using Eq. (15), we obtain the more precise value of the slope of the lines on the planar surface passing through p_1, and p_2 and passing through p_2 and p_3. Let k_1 and k_2 be the more precise values of slopes from Eq. (15) using several measurements along each two linear scanning paths respectively. Substition of k_1 and k_2 into (10) and (11), we can obtain the pan and tilt angles θ and φ respectively.

Ⅴ. Determination of the swing angle and its 3-D location

In the previous section, the pan and tilt angles were found by the use of the acoustic range data. The swing angle and engagement point of the planar surface of a pallet must be determined to perform engagement task. A simple way is the use of vision system. Vision system can easily obtain the information about edges and features once camera is orthogonal to the planar surface. The vision system can provide a 2-D description of the scene in the plane of the workspace which is incident to the optical axis of the camera.[2]

Edges are detected between regions of light intensity. The gradient or edge magnitude is calculated using Sobel operators.[2] The edge magnitude of the planar surface of a pallet is obtained by applying this operation to the image taken from the CCD camera. The image are 510×492 pixels with 256 gray levels. The image of edge magnitude is to be binary image $b(x,y)$ where x and y are image coordinates. To find the swing angle and engagement points of two slots of the pallet, we use centroid $(\bar{x}, \bar{y})$ of binary image given by Eqs. (16) and (17).

$$\bar{x} \iint_I b(x,y)dxdy = \iint x\ b(x,y)dxdy \qquad (16)$$

$$\bar{y} \iint_I b(x,y)dxdy = \iint_I y\ b(x,y)dxdy \qquad (17)$$

where the integraion is over the whole image I and $(\bar{x}, \bar{y})$ is the centroid of binary image.

Since the centroid of the image taken at a certain distance is invariant to the rotation. The normal distance, d from the centroid to an edge of the planar surface of the pallet is constant. A straight line from the centroid with the appropriate (d, ϕ) parameters fits an edge to find the swing angle ϕ using least mean square method. In our case, d is not variable because the forklift is simply moved to the fixed distance using the acoustic ranging sensor. After forklift is rotated by the swing angle, it is parallel to the planar surface of pallet. Two engagement points which are the centers of two slots located at the bottom of the pallet are found using edge features of binary image easily.

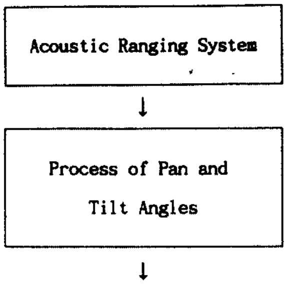
Ⅵ. Experimentation and Results

The overall experimental setup can be devided into three general categories : robot(i.e., forklift), sensors, and computer systems. The overall system configuration of the experimental setup is shown in Fig. 1.

A miniture forklift system is designed and installed on a robot gripper. The robot is a 6-axis Unimate PUMA 560 with a Mark II controller based on workstation. The programming language is VAL II, an interpretive BASIC-like language. The robot controller handles real-time trajectory modifications through its ALTER port, which requires communication of modifying position values every 28 msec. and allows modification in world or tool coordinates. This communication is provided by a dedicated real-time 68000-based Omnibyte processor.

In order to manage the complexity, the system requires a host computer to be used for supervisory control. The supervisor generates overall task commands for the robot. The dedicated work station with entry level eight-plane color graphics capability will be used as a supervisory system. Programs will be written in a modular fashion in C, augmented by UNIX system functions. The Trapix 55000 model 55/64 real-time image processor developed by Recognition Concepts, Inc., is used as a vision system. The power of Trapix 55000 is greatly enhanced by incorporating the pipeline image processor(PIP). Every subsystem is interfaced with the Micro VAX host computer.

The first experiment was the investigation of the accuracy of the acoustic sensor. The distance between the acoustic sensor and the pallet is about 45cm. A height and width of the pallet are about 23cm and 17cm respectively. Various resolutions of the horizontal and vertical scanning are examined for the proposed robot system. To reduce the effects of dispersion of the acoustic signal around edges of a pallet, range data obtained near edges of the pallet planar surface is neglected. Table 1 shows the average error percent between the actual and measured orientation and the success percent of the engagement tasks. With the resolution of horizontal and vertical scanning 1cm, the results show errors between the actual and measured orientation of approximately 2~3% on the average if the pallet planar surface has less than +/− 15 degrees of the pan and tilt angles. With these results, there were no failures when we performed engagement task 50 times for each resolution. On the average, it takes about 15 seconds to perform engagement tasks. Fig. 7 shows a functional diagram of the forklit pallet engagement process. The real system of the experiment is shown in Fig. 8, Fig. 9, and Fig. 10. Fig. 8, Fig. 9, and Fig. 10 are the robot system with multi-sensor forwith to perform engagement task, multi-sensor forklift system, edge of pallet respectively.



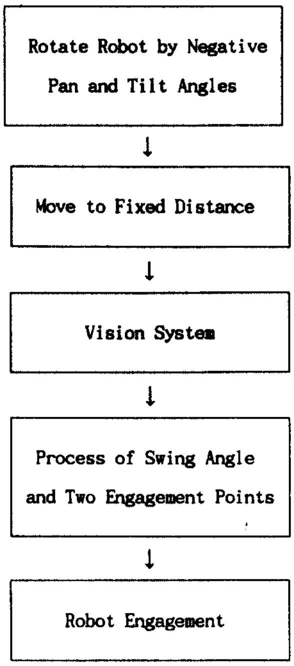


Fig. 7. The Functional Diagram of the Forklift Pallet Engagement Process

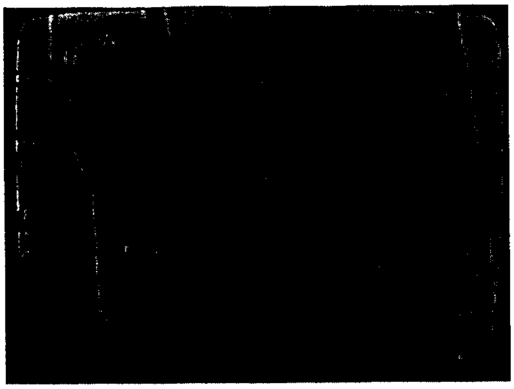


Fig. 8. The real robot system with multi-sensor forklift

Table 1. Experimental results with various resolutions

HR & VH	# of HSP	# of VSP	AEPOR	# of Trial	# of Success
0.5 cm	31	20	2.0 %	50	50
1.0 cm	15	11	2.5 %	50	50
1.5 cm	10	8	2.8 %	50	50
2.0 cm	8	6	3.0 %	50	50

Where HR is horizontal resolution, VH is vertical resolution, # of HSP is the number of horizontal scanning points, # of VSP is the number of vertical scanning points, and AEPOR is average error percent of orientation.

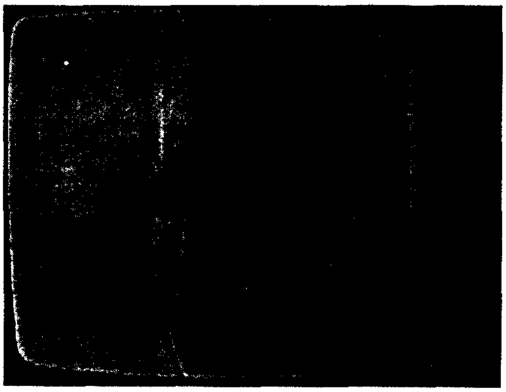


Fig. 9. The real multi-sensor forklift

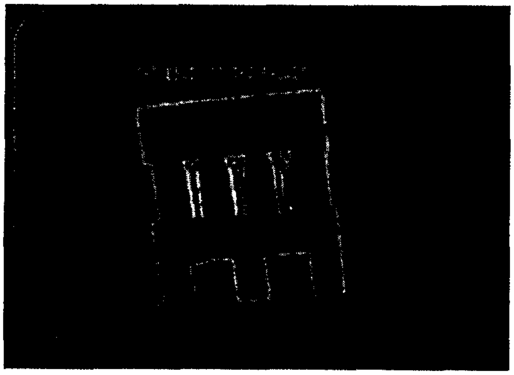


Fig. 10. Edge of a planar pallet to compute swing angle and two engagement points

Ⅶ. Conclusion

We have described a method that uses both acoustic range data and visual intensity data to locate a planar object and perform a specific task. The range data were used to find the pan and tilt angles of a planar object (i.e. pallet). The pan and tilt angles were computed with a least mean square method. The intensity data were analyzed to obtain the swing angle and the two engagement points of the pallet using the line edge fitting. The combination of the acoustic data with the visual data provides new opportunities for the simple and rapid location of the object in the 3-D space while the location of object in 3-D space would be difficult and time-consuming to obtain from visual data or range data alone.

The overall experimental results demonstrate that the system can operate in real time. Also the system has proven the robust in an unstructured environment as would be found in a real world application.

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