On line tracking of moving objects from moving platforms

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ON LINE TRACKING OF MOVING
OBJECTS FROM MOVING
PLATFORMS

by

Raveen Abhisetty

A thesis submitted in partial fulfillment
of the requirements for the degree of

Master of Science

in

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ABSTRACT

It is desired to position the end point of a conveyor belt, which carries material removed by a moving pavement trimmer, above the bed of a moving dump truck. The present report describes the analytical design and practical control of a tracking system for positioning the conveyor. Initial tests were conducted on a Unimation PUMA robot. The original pavement profiler has been modified to allow automatic computer control of both the soil removal and distribution systems. The distribution is performed by a two degrees of freedom moveable boom with a conveyor system. Two methods for non-contact target position detection were evaluated: machine vision and ultrasound. An ultrasound based target system was selected and implemented on a PUMA robot. Control software for on-line target acquisition and tracking was developed and tested. A set of ultrasound sensors and a boom rotation sensor were installed on the pavement profiler. All sensors are currently operational.
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CHAPTER 1

INTRODUCTION

Removal of hazardous radioactive soil at the Nevada test site has become a major concern for the Department of Energy (DOE), which is searching for an efficient means to remove this radioactive soil. For this purpose it needs a vehicle that would operate on rough and uneven terrains and excavate the hazardous radioactive soil from the test site and then dump this radioactive soil into the transportation vehicles for disposal.

The DOE selected the PR-500-FL pavement profiler for this project. The pavement profiler is shown in Figure 1.1. The PR-500-FL, manufactured by the Caterpillar company, was originally designed for use on roads, and all the controls on this machine are manual. These include the cutting depth of the soil and control of the conveyor boom for the discharge of soil into transportation trucks. On rough terrain, the vehicle has to be prevented from inadvertent tilting. It would be difficult for the operator to drive the vehicle safely and at the same time operate the controls of to dump the excavated soil into the moving trucks, to adjust the cutting depth according to the terrain and to balance the vehicle. This prompted the DOE to ask for the automation of some of these controls on the vehicle so that the operator can concentrate on driving the vehicle safely in the desired direction without affecting the efficient performance of the machine.
Figure 1.1 PR-500-FL Pavement Profiler

- Console Assembly
- Lower Conveyor Assembly
- Upper Conveyor Assembly
- Leg Assembly
- Cutter Assembly
The automation of some of the operations of the rotomill and the required modifications on the vehicle, are presently underway under the guidance and supervision of Dr. Georg Mauer, Associate Professor, Department of Mechanical Engineering, University of Nevada, Las Vegas. This report is primarily concerned with the automatic control of the conveyor boom. The conveyor has two degrees of freedom and can move in horizontal and vertical directions. The conveyor belt is approximately 7.5m long and 0.7m wide and is hydraulically controlled. The soil removed by the machine is loaded into the transportation vehicle with the help of the conveyor belt. The controller has to search for the vehicle and keep track of its position relative to the rotomill. When the machine is turned on for operation, it first searches for the truck and thereafter keeps tracking it.

During operation, the truck will move relative to the rotomill. Automatic boom tracking requires sensors to search for the truck, and a feedback control system which detects position changes of the truck, and which adjusts the boom such that the boom tip remains continuously above the truck bed.

The problem of automatic control of the conveyor boom is very much similar to the target tracking problem in robotics, where a moving object is tracked using vision sensors or acoustic sensors. Development of intelligent robots require research on new sensors and software necessary for their use. Among the sensors now used for target tracking are vision sensors, optical sensors and acoustic sensors.
LITERATURE REVIEW

Visual tracking

Vision is by far our most powerful tool. There has been much research over a number of years addressing visual tracking of moving objects. Many industrial systems employ a camera mounted over work area for viewing, enabling the position and orientation to be detected. Various methods are in use for this purpose. Allen [1] used two fixed cameras that can image a scene containing moving object. This gave him three-dimensional position of the moving object that helped in tracking and then grasping a moving object. Lee and Whon [2] used an image differencing method to track the motion of the moving object. Brown[3] has set up a gaze control system that links a robotic head containing binocular cameras with a servocontroller that allows one to maintain a fixed gaze on a moving object. Rao and Durrant-Whyte [4] set up a kalman filter based decentralized tracking system that tracks moving objects with multiple cameras. Nikolaos [5] used the combination of control and vision for visual tracking of a moving target with a camera mounted on a robot.

Artificial Neural Networks (ANN) are used with vision to guide autonomous vehicles. Miller [6] used a Cerebellar Model Arithmetic Computer(CMAC) neural network structure to track an object on a moving conveyor using video camera. Currently a lot of research is done at Carnegie Mellon University on NAVLAB, which is their autonomous vehicle using ANN with vision [7]. Another project, ALVINN (Autonomous Land Vehicle in a Neural Network), uses ANN with images from a video camera and a laser range finder as input gives out direction the vehicle should follow as the output.
Ultrasonic Sensors

In recent years noncontact sensing based on ultrasonics has increasingly attracted attention in the field of robotics. Ultrasonic sensors are used in many experimental mobile robots. The main attractions of ultrasonic systems are low cost, ease of implementation, and inherent safety. A lot of research is underway for the development of mobile robots for health care applications. Borenstein and Koren [8] used ultrasonic sensors for the detection of an obstacle. They developed a mobile robot system, which can do various tasks for the physically disabled. Kadonoff [9] used ultrasonic sensors to measure the range and bearing to the wall for position estimation of wall following mobile robot. Knoll [10] used ultrasonic holography techniques for determining the shape and structure of the objects. Maqueira [11] used ultrasonic sensors to develop an automatic seam tracking system. He used a single transducer to obtain geometrical information required to track joints in two-dimensional space. Ultrasonic sensors are also used in the area of underwater marine applications for detecting and tracking objects.

Optical range finders

Recent advances in sensing technology resulted in optical range finders to do target detection and tracking. Infrared search and tracking systems are usually used to locate targets in the clear or sky background. Infrared systems are used in a number of missile seekers to track targets for missile guidance and target interception. Moser [12] developed a simple infrared ranging system for mobile robot navigation and collision avoidance.
State of the Art

Recently there has been an increasing interest in the development of robot systems capable of using many different sources of sensory information. A single sensor can only provide partial information about an environment. Diverse information from many different sources can be used to overcome the limitations inherent in the use of single sensors. This diverse information can be integrated and utilized to overcome the limitation of any one sensor system. Durrant-Whyte [13] described a technique for modeling sensors and the information they provide. Flynn [14] combined an ultrasonic and an infrared sensor for mobile robot navigation in a complementary fashion where the advantages of one compensate for the disadvantage of the other. Shashank [15] presented a method to obtain the position and orientation of an object through measurements from multiple sensors.
CHAPTER 2

PROBLEM STATEMENT

The rotomill pavement profiler will be used to excavate radioactive soil to varying levels of depth depending on the amount of ground penetration of contaminants. This excavated soil should be dumped into the transportation vehicle by means of the conveyor boom. The conveyor boom has two degrees of freedom. The operator has to monitor and adjust a number of controls including the conveyor boom while the vehicle is in operation. Automatic control of the conveyor boom will help the operator to monitor the other controls and drive the vehicle more safely.

The conveyor boom should always be above the bed of the truck to dump the soil into the truck. This task can be accomplished by tracking the truck location relative to the rotomill and changing the position and orientation of the boom according to the change in position and orientation of the truck.

The following two methods are under consideration, and to be investigated in the laboratory.

2. Ultrasonic target tracking.

One of these methods is to be selected for implementation on the vehicle, and to be installed and tested.
CHAPTER 3

VISUAL TRACKING

Machines are used by humans to perform certain tasks with the assistance of an operator who controls and directs the machine. Automation of machines and manufacturing machines that can see is one of the fields where much research has been focused in recent years. It is difficult to impart the total capability of the human visual system to a single machine, but machines can be manufactured to perform a specific task. A machine with intelligent vision capabilities and with a capacity to reason with data without the aid of human assistance can be applied in many areas. It would be advantageous for a machine to have intelligent vision capability when it is performing a task of hazardous nature.

In order to recognize an object in the scene, it is necessary to have some sort of predefined description or model of the object to refer to. The simplest approach may record a few qualitative and geometric features but the more sophisticated approaches, such as those originally developed for Computer Aided Design applications, can record both complete low level geometric details of the object and higher level relationships. A schematic diagram of a vision system is shown in Figure 3.1.
Figure 3.1 Schematic diagram of visual tracking system
Image acquisition

The first stage of any vision system is the image acquisition stage. After obtaining the image, various image processing methods are applied to the image to perform many different vision tasks. However, if the image has not been acquired satisfactorily then the intended tasks may not be achieved even with the aid of image enhancement.

The basic two-dimensional image is a monochrome (gray scale) image that has been digitized. The original image is a two-dimensional light intensity function $f(x, y)$ where $x$ and $y$ are spatial coordinates and the value of $f$ at any point $(x, y)$ is proportional to the brightness or gray value of the image at that point. A digitized image is one in which the spatial and gray scale values have been made discrete. Samples of light intensity are measured across a regularly spaced grid in $x$ and $y$ direction and the sample values are recorded. The 256 sets of different possible intensities are commonly employed.

In our experiments a charge-coupled device (CCD) video camera is used as an image input device. The output is a video signal and this output must be digitized. A device known as frame grabber usually accomplishes this task. A frame grabber digitizes the incoming video signal into discrete pixels by sampling the analog signal at appropriate intervals and converting it to a digital value. During this process, it stores the data line by line in its own memory. The stored frame can easily be transferred to computer memory.
Image processing

Image processing is typically concerned with taking an array of pixels as input and producing another array of pixels as output, which is better than the original array. Usually, the aim of this processing is to make the image more intelligible and useful to the human eye and brain. For example, image processing may remove noise, it may improve the contrast between light and dark features in the image, it may remove the blurring in an image caused by movement of the camera during image acquisition, or it may correct for geometrical distortions caused by the lens.

Image processing can be broadly divided into two categories
1. Real space method
2. Fourier space method.

In the real space method the input pixel array is processed directly to produce the output array. In the Fourier space method, a new representation of the input data, derived by performing a Fourier transformation, is processed and finally an inverse Fourier transform is performed on the resulting data to give the final output image.

Noise reduction

The various spurious effects of a local nature in the image, caused perhaps by noise in the image acquisition system, or arising through of the transmission of the image, can be reduced either by considering the real space image or its Fourier transform.

Neighborhood averaging

The simplest approach for the noise reduction is neighborhood averaging, where each pixel is replaced by the average value of the pixels contained in its neighborhood.
For example, consider a 3x3 group of pixels centered on the given pixel. The value of the central pixel is determined by the average of these nine pixels. If any one of the pixels in the neighborhood has a faulty value due to noise, the fault will now be smeared on the neighboring pixels, thus making it much less noticeable. Unfortunately, other information in the image also gets smoothened, resulting in a blurred image. As the size of the neighborhood is increased, the image is more blurred.

Threshold averaging

In threshold averaging, if the value of the pixel is not too far from the neighborhood average, it is replaced by the average value otherwise it is kept unchanged. There will be a large change in pixel values near an edge and pixels on both sides of it will not be close to the average value. This process still smoothen pixel values in the regions where there are only small changes, but avoids smoothing edges. The blurring of the image is reduced and a large neighborhood can now be used.

Median filter

In this method the pixel is replaced by the median pixel value in the neighborhood. This approach preserves the sharpness of the edges. If there are large amounts of noise in an image, more than one pass of median filtering may be used.

Contrast enhancement

Sometimes captured images display only a limited range of intensities due to poor lighting or various other causes. Enhancing the contrast increases the difference in intensity between the pixel values and makes the image more understandable.
**Edge detection**

An edge may be regarded as a discontinuity, as a boundary between two dissimilar regions in an image, where there is a sudden change in gray level indicating the end of one region and the beginning of another. Edges provide strong clues to the shape of the object. Furthermore, if edge information is used in conjunction with other methods it is possible to develop some powerful vision applications. There are many edge detection methods. Sobel, Roberts, Cross, and Diagonal filters detect edges oriented in all directions. Horizontal, vertical, left diagonal, and right diagonal filters detect edges oriented in the direction for which they are named. Any one of these methods can be used for edge detection.

**Object Identification**

Recognition is the main goal of many vision systems. After performing the noise reduction, contrast enhancement, and edge detection operations we get a clear image of what has to be recognized. In order to recognize an object we must have some notion of the object's shape. This information is usually provided by the geometric model of the object stored in the computer. Having recognized the object, the position and orientation of the object can be found. This information can be used for object manipulation, tracking, navigation, inspection, etc. In the present application this information is needed for tracking purposes. Once the position and orientation of the target have been detected this information can be used to change the position and orientation of the machine to which the camera is hooked up, so that the camera can view the target and track it.
Experiment

A frame grabber board is installed within a personal computer and connected to a camera for image acquisition. Global Lab Image Software was used for Image Processing. The image of an object in the laboratory is captured and this image is stored in the computer.

Image Processing is done to remove the noise, enhance the contrast of the image and sharpen the image. This is done by using the above described methods for noise reduction and contrast enhancement. The next step is edge detection. Geometric information about the captured object is stored in the computer. After detecting the edges and knowing the gray scale range of the object, the object is recognized with the help of the available geometric information.

Three different cases analyzed under different conditions for object recognition are presented here. In the first case the object was a rectangular frame with a fine surface under good lighting conditions. The second and third case were more general case with ordinary lighting conditions and a rough surface.

Case (1):

A picture of a rectangular light frame was captured in the laboratory. The lighting conditions in the laboratory were good and the light frame had a fine surface. This image is shown in Figure 3.2. The good lighting conditions produced a uniform gray scale values, so that further analysis led to conclusive results. In Figure 3.2 three frames numbered 1, 2, and 3 had to be identified. All three frames had a uniform gray scale range. After performing the image analysis operations and object recognition were
done, and the object could be identified easily. Figure 3.3 shows the results of the edge detection operation.

Case (2):

A picture of a rectangular block was captured in the same way as described before, but in this case the light conditions were poor which resulted in more variation in the gray scale range. The image is shown in Figure 3.4. A number of dark spots can be observed on the surface of the rectangular block. If the surface of the rectangular block had been smooth these black spots would not have been there. The range of gray scale tones was very large and was not uniform because of these black spots. This can also be observed clearly in Figure 3.5 after performing the edge detection operation. Image analysis was done but the object could not be identified.

Case (3):

In this case a similar analysis was done on the image of the same rectangular block, with the camera recording the image from a different location. This gave an image with again different gray scale. The captured image is shown in the Figure 3.6. Many black spots can be seen on the image of the block because the surface of the block was not smooth. There was a significant variation in the gray scale range of the picture. The object could not be identified after performing the image processing and edge detection operation on the image. Figure 3.4 and 3.6 are images of the same rectangular block captured under same lighting conditions but at a different angle. Each image had a different gray scale range.

When an object moves from one position to another position in natural light
conditions, there will a lot of variation in the gray scale range as the light condition vary with the moving object. Therefore, in general conditions it would be very difficult to achieve the desired results using Global Lab Image software.
Figure 3.2  Image of a Light Frame Captured with the Camera
Figure 3.3 Image of the Light Frame in Figure 3.2 After Edge Detection
Figure 3.4 Image of a Rectangular Block Captured with the Camera
Figure 3.5 Image of the Rectangular Block in Figure 3.4 After Edge Detection
Figure 3.6 Image of the Rectangular Block taken at a Different Angle
CHAPTER 4

ULTRASONIC SENSORS

In recent years, sensing based on ultrasonics has increasingly attracted attention in the robotics community. Ultrasonic sensors are simple in construction, mechanically robust and provide accurate distance measurement at low cost. They can be often used in environments where the other sensors tend to fail to provide required information. Moreover, the basic arrangement is very simple. An ultrasonic transmitter generates a short sound impulse causing a longitudinal wave to propagate away from the sensor. This wave is reflected by solid objects and travels back to the sensor waiting for the return echo. The sensor detects the time elapsed between emission and return. This output is used to detect the presence, or distance of the target from the sensor.

Ultrasonic tracking is affected by several factors including the target surface, size of the target, the distance and the angle at which the target is placed with respect to the sensor. Environmental conditions such as temperature, humidity, gases and pressure also affect the measurement.

The ideal target surface is hard and smooth, producing a larger echo signal than a soft or rough target surface. A weak echo decreases the accuracy of the sensor. The orientation of the target surface facing the ultrasonic beam is also an important factor. The portion perpendicular to the sensor returns the echo. Figure 4.1 shows one part of
the wavefront, emitted by the ultrasonic transceiver $S$ towards a parallel surface of an
obstacle. Most of the sound energy is reflected perpendicular to the surface and will be
detected by $S$, while only a small percentage of the energy is scattered in other directions.
However, if the surface of the target is not normal relative to the sensor $S$ as in Figure
4.2, then only a small amount of energy will be reflected towards $S$.

The shorter the distance traveled by the sound waves, the greater is the intensity
of the signal from the target surface. Therefore, as the distance increases, the target
requires better reflective characteristics to return a sufficient echo. A large target has
greater surface to reflect a signal. The range of ultrasonic sensors varies from one sensor
to another sensor. Depending upon the distance between the sensor and the target a
particular sensor is chosen so that the target is always within the range of the sensor.

**Temperature compensation for the ultrasonic sensors**

The changes in air temperature will also change the speed of the sound. A
temperature compensator will help compensate for this change. DCU-7 ultrasonic sensors
manufactured by Lundhal Instruments Inc. are being used for tracking in this purpose.
These are available in 2 versions DCU-7-X-X-T which contains an internal thermistor and
DCU-7-X-X which should be used with external temperature sensor. DCU-7-X-X-T are
used here. This is used in applications where an external temperature sensor is not
practical or available. This is best suited in stable environment shielded from direct
radiation. Because temperature sensor is internal it is slow in responding to sudden
temperatures. This internal sensor is also affected by how long the sensor runs
continuously and direct radiation.
Figure 4.1 Reflections of ultrasonic waves from target surface perpendicular to ultrasonic sensor axis.

Figure 4.2 Reflections of ultrasonic waves from target surface when angle $\alpha$ is large.

S  Ultrasonic sensor
T  Target surface
CHAPTER 5

SELECTION OF SENSOR SYSTEM FOR ROTOMILL

The rotomill will be operated on rough and uneven terrains while operating on off-road conditions. The tracking system should be designed in such a way that it can function effectively under all circumstances. It is very much certain that the environment in which the rotomill will be operating will be full of dust. The tracking system should be robust enough to withstand these rough conditions and produce satisfactory results.

Two kinds of tracking systems are under consideration for this purpose.

2. Ultrasonic target tracking.

In vision based tracking system the image of the moving target will be captured using a video camera and this image will be stored in the computer to identify the object and detect the motion. To capture a clear picture of the moving target the surrounding atmosphere should be clear with good light conditions. The rotomill operation will generate a lot of exhaust fumes and dust. This will definitely affect the quality of the image which in turn will make the image processing and subsequent object identification difficult. Also, it is not certain that the light conditions will always be good when the vehicle is under operation. In the case of poor light conditions special arrangements have to be made to obtain an image of good quality. The video camera has to be handled with
care. The electronic system is complex and requires proper maintenance.

Taking all these things into consideration it is better to use some other kind of tracking system robust enough to withstand all these rough conditions and which require very little maintenance. Ultrasonic sensors are simple in construction, mechanically robust, are comparatively cheap and require little maintenance. These sensors are used in a wide variety of applications. Hence a tracking system using ultrasonic sensors will be best suited for this kind of application to produce good results.
PUMA Robot

The PUMA robot is designed to adapt to a wide range of applications. The basic units are the teach pendant, software, controller, peripherals, and robot arm. The system software that controls the robot is stored in the computer memory located in the controller, which also houses the operating controls for the system.

The following two methods can be used to teach the robot arm. In the first method, the teach pendant may be used to manually direct the movements of the robot through each step of the task. These steps are recorded and then stored in the computer memory. The second method is to write a program using software instructions.

The robot arm is the mechanical component of the system with six degrees of freedom. Each member of the robot arm is connected to another member at a joint, much like a human arm. Through each joint one or more axes pass around which the members of the arm rotate. The members of the robot arm are shown in the Figure 6.1. The robot arm executes the instructions transmitted to it by the controller. It is sufficiently flexible execute wide variety of tasks.
Figure 6.1 PUMA robot arm
**Robot Control Software**

The PUMA operates with a high level language called VAL-II. VAL-II is a sophisticated programming language developed for assembly, and permits complete robot control. VAL-II commands can be issued interactively on a monitor, or through VAL-II programs. It has communication capabilities with other computers as well as with supervisory computer systems. The VAL-II PC supervisor interface software permits an IBM PC to control the robot. It uses RS-232C cabling between the PC and the robot. The DDCMP (Digital Data Communications Protocol) driver and file server program provides a generic interface between an MS/PC-DOS application program and the VAL-II supervisory port. The interface also contains the routines necessary to format and transfer PC files to and from VAL.

The user developed application program functions as a completely independent program under MS-DOS. The only association between the supervisor and the application is the DOS interrupt vector in low memory that provides access to all supervisor services. Application access to the supervisor is through the use of service request blocks presented to the supervisor service routine through the address contained in the interrupt vector location. Both the supervisor and the application must always use the same interrupt vector address.

**Target Tracking**

Two ultrasonic sensors, sensor(0) and sensor(1) are attached to the end effector of PUMA robot. These sensors are connected to a real time interface board on the PC. It is desired to locate the edge of a box shaped object (rear surface of the truck). Sensor(0)
Figure 6.2 Tracking Position of Ultrasonic Sensors Hooked on the PUMA Robot.

S0, S1 Ultrasonic Sensors
T Target
P PUMA Robot
will point to infinity, no object will be present within the range of this sensor. Sensor(1) will capture the target surface and measure its distance. The target is searched by rotating the robot. If there is no object within the range of both the sensors or if both sensors detect the object, the robot is rotated until it locks on to the desired tracking position again.

The process of searching for and tracking the target is controlled automatically from the PC by a program written in 'C' language. The program TRACK.C, has three main components.

1. Building communication between the PC and the robot
2. Searching for the target and
3. Tracking the target.

After starting TRACK.EXE, a self-explanatory menu appears on the screen, by which the user establishes communication between the PC and the robot. After establishing communication, a search algorithm is started.

The robot starts searching for the target from a fixed position each time the program is executed. Initially the robot keeps moving to its right till it finds the target. If the robot joint reaches the limit before finding the target, it starts searching for the target in the opposite direction. If the robot does not find the target in this direction till it reaches the limit, it starts searching for the target moving in the opposite direction. This process is continued till the target is found. When the target is found and if the sensors are in tracking position i.e., if sensor(0) is pointing to infinity and if sensor(1) is pointing the target, the sensors will keep tracking the target and a message will appear on
the screen saying that the sensors are tracking.

If both sensors detect the target, a message to this extent appears on the screen. A command is issued from the PC to the robot to rotate the robot to its left, and repeated until the sensors are in right position. A message appears saying that the object is being tracked.
CHAPTER 5

CONTROL SYSTEM MODEL

This chapter discusses the construction of the mathematical model of the system to be controlled. The conveyor boom of the rotomill is an elastic structure 10m long, and with a total mass of approximately 1500kg. The boom exhibits noticeable vibrations when actuated by one of the hydraulic pistons. A lumped-parameter system was developed as an approximate model of the boom dynamics, see Figure 7.1. The mathematical model of the conveyor boom is constructed considering it as two masses connected by means of a torsional spring. The boom is attached to the structure at A by a rotational joint. Mass $m_1$ is distributed over length $l_1$, its center of mass is acting at $l_1/2$. Mass $m_2$ is of length $l_2$, its center of mass is located at $l_2/2$. A constant torque $\tau$ is applied at the fixed end A. The torsional spring at B couples both lumped parameter masses.

The equations of motion for this system were developed using Lagrange’s method.

Lagrange’s Method:

The moment of inertia of mass $m_1$ at its center of mass is:

$$ I_1 = \frac{1}{12} m_1 l_1^2 $$
Figure 7.1 Mass $M_1$ and Mass $M_2$ Connected by a Torsional Spring
The moment of inertia of mass $m_1$ is

$$I_2 = \frac{1}{12}m_2 l_2^2$$

displacement of mass $m_1$ in $x$ direction is

$$x_1 = \frac{l_1}{2} \cos \theta_1$$

displacement of mass $m_1$ in $y$ direction is

$$y_1 = \frac{l_1}{2} \sin \theta_1$$

displacement of mass $m_2$ in $x$ direction is

$$x_2 = l_1 \cos \theta_1 + \frac{l_2}{2} \cos \theta_2$$

displacement of mass $m_2$ in $y$ direction is

$$y_2 = l_1 \sin \theta_1 + \frac{l_2}{2} \sin \theta_2$$

Kinetic energy of mass $m_1$

$$T_1 = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} I_1 \dot{\theta}_1^2$$

$$= \frac{1}{2} m_1 (\dot{x}_1^2 + \dot{y}_1^2) + \frac{1}{2} I_1 \dot{\theta}_1^2$$

$$= \frac{1}{6} m_1 l_1^2 \dot{\theta}_1^2$$
The kinetic energy of mass $m_2$ is

\[ T_2 = \frac{1}{2} m_2 v_{22}^2 + \frac{1}{2} I_2 \dot{\theta}_2^2 \]

\[ = \frac{1}{2} m_2 (\dot{x}_2^2 + \dot{y}_2^2) + \frac{1}{2} I_2 \dot{\theta}_2^2 \]

\[ = \frac{1}{2} m_2 (l_1^2 \dot{\theta}_1^2 + \frac{1}{3} l_2^2 \dot{\theta}_2^2 + l_1 l_2 \dot{\theta}_1 \dot{\theta}_2 \cos (\theta_2 - \theta_1)) \]

The total kinetic energy is $T$

\[ T = T_1 + T_2 \]

\[ T = \frac{1}{6} m_1 l_1^2 \dot{\theta}_1^2 + \frac{1}{2} m_2 l_1^2 \dot{\theta}_1^2 + \frac{1}{6} m_2 l_2^2 \dot{\theta}_2^2 + \frac{1}{2} m_2 l_1 l_2 \dot{\theta}_1 \dot{\theta}_2 \cos (\theta_2 - \theta_1) \]

The potential energy of the torsional spring is

\[ V = \frac{1}{2} k_1 (\theta_2 - \theta_1)^2 \]

Lagrange’s equation is

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_i} \right) - \frac{\partial L}{\partial \theta_i} = Q_i \]

\[ L = T - V \]
Differentiating with respect to $\theta_1$ gives
\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_1} \right) - \frac{\partial L}{\partial \theta_1} = \left( \frac{1}{3} m_1 l_1^2 + m_2 l_1^2 \right) \ddot{\theta}_1 + \left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_2 + k(\theta_1 - \theta_2)
\]
\[
\frac{1}{3} m_1 l_1^2 + m_2 l_1^2 \ddot{\theta}_1 + \left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_2 + k(\theta_1 - \theta_2) = \tau - R(\theta_1 - \theta_2)
\]
\[
\left( \frac{1}{3} m_1 l_1^2 + m_2 l_1^2 \right) \ddot{\theta}_1 + \left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_2 + R(\theta_1 - \theta_2) + k_i(\theta_1 - \theta_2) = \tau
\]

Differentiating with respect to $\theta_2$ gives
\[
\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}_2} \right) - \frac{\partial L}{\partial \theta_2} = \left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_1 + \left( \frac{1}{3} m_2 l_2^2 \right) \ddot{\theta}_2 + k_i(\theta_2 - \theta_1)
\]
\[
\left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_1 + \left( \frac{1}{3} m_2 l_2^2 \right) \ddot{\theta}_2 + k_i(\theta_2 - \theta_1) = R(\theta_1 - \theta_2)
\]

The equations of motion are
\[
\left( \frac{1}{3} m_1 l_1^2 + m_2 l_1^2 \right) \ddot{\theta}_1 + \left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_2 + R(\theta_1 - \theta_2) + k_i(\theta_1 - \theta_2) = \tau
\]
\[
\left( \frac{1}{2} m_2 l_1 l_2 \right) \ddot{\theta}_1 + \left( \frac{1}{3} m_2 l_2^2 \right) \ddot{\theta}_2 + R(\theta_2 - \theta_1) + k_i(\theta_2 - \theta_1) = 0
\]
Let

\[ A = \frac{1}{3}m_1 l_1^2 + m_2 l_1^2 \]

\[ B = \frac{1}{2}m_2 l_2 \]

\[ C = \frac{1}{2}m_2 l_2 \]

\[ D = \frac{1}{3}m_2 l_2^2 \]

\[
\begin{vmatrix}
As^2 + Rs + k & Bs^2 - Rs - k \\
Cs^2 - Rs - k & Ds^2 + Rs + k
\end{vmatrix}
\]

\[
\begin{vmatrix}
\theta_1(s) \\
\theta_2(s)
\end{vmatrix}
= \begin{vmatrix}
U(s) \\
0
\end{vmatrix}
\]

The transfer functions result as

\[
\theta_1(s) = \frac{U(s) (Ds^2 + Rs + k)}{(As^2 + Rs + k)(Ds^2 + Rs + k) - (Bs^2 - Rs - k)(Cs^2 - Rs - k)}
\]

\[
\theta_2(s) = \frac{-U(s) (Cs^2 - Rs - k)}{(As^2 + Rs + k)(Ds^2 + Rs + k) - (Bs^2 - Rs - k)(Cs^2 - Rs - k)}
\]
These equations are used to create an executable file and run the file on MATRIX-x to find the response of the system. Constant torque is the input to the system. The output is shown in Figure 7.2.

A model is built on MATRIX-x for ultrasonic sensor tracking. The block sensor_search_0 is sensor one and the block sensor_search_1 is sensor two. Sensor one will point toward infinity without any object in its range and sensor two will point toward the target. This is the tracking position for the sensors. Of the four logical blocks R_L, TT, R_L, and L_R only one is true at a time. Initially, when the search for target is on the conveyor is moved from right to left to search for the target. If there is no target in the range of both the sensors the block R_L is true. If both the sensors are pointing to the target then the block L_R is true. If sensor one is towards infinity and sensor two is towards target then block TT is true. The model is shown in Figure 7.3.
Figure 7.2. Response of the System with Constant Torque Input. $\tau = 10000 \text{ N-m rad}$. 
Figure 7.3 Model built on Matrix-x for ultrasonic tracking
CHAPTER 8

MODIFICATIONS ON THE VEHICLE

In this chapter, the work done on the PR-500-FL pavement profiler for the installation of the sensors is presented. Parts are designed and welded on to the vehicle to install the sensors at appropriate positions. Two ultrasonic sensors and two angular displacement transducers are installed on the vehicle to track the moving target and detect the conveyor position. The locations of the ultrasonic sensor and angular transducer installations on the vehicle are shown in figure 8.1.

Two DCU-7E-16 ultrasonic sensors manufactured by Lundahl Instruments Inc. are used. The operating distance of these sensors is 2-16ft., and the operating temperature range is from -20°C to +60 °C. The guidelines for mounting these sensors, wiring, electrical specifications, and other details are explained in the operating manual. The steel plate shown in figure 8.2 is welded on to the vehicle as shown in figure 8.4. The ultrasonic sensors are fixed on to this plate. The electrical wiring from the ultrasonic sensors goes into the cabin of the vehicle where the computer is installed. The signals from the two ultrasound sensors are connected to A/D input channels 12 and 13.
Figure 8.1 Modified PR-500-FL pavement profiler
Figure 8.2 Plate Designed to Install Ultrasonic Sensors on the Vehicle
Figure 8.3 Ultrasound Sensors Fixed on the Plate
Figure 8.4  Figure showing ultrasonic sensors installed under the conveyor boom of the vehicle.
The power supply to the sensors is provided from the battery of the vehicle located at the rear end of the vehicle.

The conveyor has a horizontal swing of \(-75^\circ\) to \(+75^\circ\) and a vertical swing of \(-30^\circ\) to \(+30^\circ\). When the conveyor is moved either manually or automatically, the operator should be informed just before the conveyor reaches its limit. The angular displacement transducers provide accurate and reliable angular position information of the conveyor. Two angular displacement transducers model 0605 manufactured by Trans-tek Inc. are used. One provides information about horizontal angular position, and the second one is used for vertical angular information. The operating range for these transducers varies form \(12^\circ\) to \(300^\circ\), and the operating temperature is \(0\ ^\circ\text{C}\) to \(70\ ^\circ\text{C}\). The guidelines for mounting these sensors, wiring, electrical specifications and other details are explained in the operating manual.

The bracket shown in figure 8.5 is welded to the vehicle as shown in figure 6.6. This transducer will provide information about the horizontal angular position of the conveyor. A steel rolled pin is press fit into drilled hole on the vehicle. The hole is drilled at the center of rotation about the vertical axis. This is shown in figure 8.6. A flexible coupling connects the fixed steel rolled pin to the rotating shaft of the angular displacement transducer.

The part shown in figure 8.7 is used to mount the second transducer, which detects the up/down motion of the conveyor. provide information about the vertical angular position of the conveyor. A steel rolled pin is press fit into the drilled hole on the vehicle. This is shown in Figure 8.8. End A of long aluminum rod, Figure 8.9 is
Figure 8.5 Bracket for Horizontal Angular Displacement Encoder
Figure 8.6  Horizontal angular displacement encoder installed on the vehicle
Figure 8.7 Housing for Vertical Angular Displacement Encoder
Figure 8.8 Long rod that connects the pin and the vertical angular displacement transducer
Figure 8.9 Installation of Vertical Angular Displacement Encoder
Figure 8.10  Vertical angular displacement encoder installed on the vehicle
fixed to the shaft of the encoder with a set screw. A slot is provided for the pin to slide in the rod. As the conveyor moves up/down the pin will slide in the slot and the rod will rotate the shaft of the encoder. This will give the position of the conveyor.
CHAPTER 9

RESULTS AND CONCLUSIONS

A tracking system by which a movable arm can follow a moving target was designed and tested. Two types of non-contacting sensor system analysis were evaluated for reference signal generation and feedback control:

(a) Vision systems and

(b) Ultrasound range detection

An ultrasound tracking system consisting of two ultrasound detectors was selected for implementation. A control algorithm for target edge search and real time tracking control was developed. The complete tracking system was implemented and tested on a PUMA robot in the laboratory. The hardware part of the rotomill tracking system was designed and installed on the rotomill. All sensors and actuators required for tracking are presently operational.

Recommendations:

It is recommended to port the software to the rotomill controller and to conduct field tests before deployment of the rotomill in contaminated areas.


APPENDIX

List of files

1. IMAGE.SCR
2. TRACK.C

IMAGE.SCR is a script file. Image analysis can be done on an image by loading this file into Global Lab Image and then running it. Object identification is done after performing noise reduction, contrast enhancement, edge detection operations on the image. The information about the object to be identified is stored in the script file.

TRACK.C is a program written in ‘C’. This program when executed will build the communication between the PC and the robot and search for the target and after locating the target it keeps track of the target by changing the position of the robot arm according to the change in the position of the target.