Abstract
This report describes the proposed design and development strategy for implementing a control system to balance a ball on a plate. A pan-tilt device is placed on its side so as to create a tilt-tilt mechanism capable of moving a ball within an X-Y plane. A resistive touch pad is placed on the plane to allow the measurement of the location of said ball. Dynamic modeling of this system allows the creation of a digital controller capable of placing the ball at certain locations or following a preset path. The project goal is to create a system capable of moving the ball at a rapid rate of speed in any of several predefined complex paths with precision and accuracy.

Team 1

Introduction

The goal of this project is to develop a ball-on-plate balancing system, capable of controlling the position of a ball on a plate for both static positions as well as smooth paths. We intend that the initially horizontal plate will be tilted along each of two horizontal axes in order to control the position of the ball. Each tilting axis will be operated on by an electric motor. Each motor will be controlled using software, with a minimum of position feedback for control.

After an extensive search, few systems of similar scale were found. The ball-on-beam system, a 1-dimensional similarity to the ball-on-plate, however, is a classic control problem, and has been studied in great detail, and solved a great many ways; PID control, optimal control, fuzzy-logic controllers, etc. The fuzzy-logic controllers would seem to be the current state of the art, however classical approaches using discrete approximations are certainly adequate, if not preferred for their relative ease of implementation. Two ball-on-plate systems were uncovered during the search: one, developed at Rensselaer Polytechnic Institute by Professor Kevin Craig [3] using a similar method to that which we intend, and another at the University of Newcastle, Australia, which was developed using image processing techniques in conjunction with a textbook by Professors Graham Goodwin, Stefan Graebe and Mario Salgado [4]. While this would seem to be a short list, the ball and beam system seems to be a more popular and less structurally complex system to implement.

The aim of this project will be to create a ball-plate system using a resistive touch sensor to allow the movement of a ball by means of automatic control. The system should have accuracy of < 2% in the placement of the ball on the screen, as well as the ability to move the ball from one end of the plate to the other in less than 2 seconds (long side). Overshoot should be minimal, to reduce the chances of losing the ball off of the plate or incurring damage to the touch element due to striking the physical structure of the system.

Team 2

The goal of this project is to build a tracking system that may be used for many purposes. These include everything from military targeting to household safety to sporting events. The motivation for this design is to have a versatile yet accurate system to complete a variety of functions. The expected end users for this product vary with the different purpose behind this design. For example, the original idea behind this design was to track a football as it moves across a field. In this case, the main users of this technology will be in the sports and recreation area.

The function requirement for the Data Acquisition System (DAS) is the building of the signal strength meters, a transmitter to be placed on the tracked object, and amplifiers to be attached to each of the signal strength meters. The signal will then be converted using analog to digital converters. These are the main parts of the DAS component of the project. The signal strength meters will continuously track the object and locate its precise position within the space of travel, which is 10’ x 10’ x 10’. There will be six meters evenly spaced in the defined area of motion. Each sensor will be contained in a small box of a size yet to be determined. The location of the sensors are as follow: one on the origin (0,0,0), one 2’ above the floor (in the middle) on the front wall of the defined box, one 4’ above the floor (in the middle) on the right wall, one 6’ above the floor (in the middle) on the back wall, one 8’ above the floor (in the middle) on the left wall, and one on the left most upper corner of the box (10,10,10). Figure 1 shows a graphical interpretation of the previous statement.
There have already been many systems that have been built for the purpose of object-tracking; however, their applications have been limited in scope. Many have relied upon visual recognition of objects to be tracked within a certain distance. An example of this would be the Logitech QuickCam Orbit which is designed to use face-tracking software to follow a user as they move in front of the camera.

This system, however, will be based upon a tracking/prediction sensor system that will track a transmitter within a designated area. Once the generalized positions of the object are known over a range of time, the pan-tilt mechanism may be adjusted to follow the object through its predicted range of motions, while continuously checking that the object is indeed following the prediction. Upon determination of a variance in the predicted path, a new prediction will be made to follow the new path. The purpose of this prediction will be to follow the object with the smoothest possible motion as the camera tracks the object through its environment (See Appendix B-1).

The tracking system itself will be controlled by a C program set up in MatLab and Simulink. This program will then be downloaded to the computer which controls the motors. The program will take the inputs from the sensors as well as the current motor angles to compute where the camera should focus. The controller will consist of two second order PID controllers (one for each motor). The two motors will essentially perform independent of one another, so the controllers themselves may be treated as two separate systems.

A quick search on the uspto.gov website verified that there are no current patents for this type of design.

**PRELIMINARY SPECIFICATIONS**

- DAS Operable Range: 10 x 10 x 10 (in ft)
- Logical signal progression (No null values or outliers)
- Amplification of signal to a range of 0 to 5V
- Low voltage, low power transmitter
- Steady signal meter voltage, when transmitter location is held constant
<table>
<thead>
<tr>
<th>Controller Pan range of 140 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt range of 130 degrees</td>
</tr>
<tr>
<td>Camera height of 3 feet</td>
</tr>
<tr>
<td>Camera distance of out edge of area is 2 feet</td>
</tr>
<tr>
<td>Camera maximum acceleration and deceleration: Yet to be determined</td>
</tr>
</tbody>
</table>

**Objective**

The goal of the ball-plate system will be to initially create a system that can hold a ball in a static position on the plate. From there, the goal will then be to be able to move the ball around the plate in varying defined motion paths. The system should also be able to compensate for disturbances in the intended motion path of the ball, as well as disturbances to the physical support system.

Initially, the desire of the team was to design a control system that could traverse a maze using the ball-plate system, using image processing to view the maze and plot a solution. However, given the processing power and estimation inherent to image processing techniques, as well as the team’s lack of experience with the theory behind these techniques, this was abandoned. The traversal of a maze might still be possible, however, the traversal would be based on a known set of moves, as opposed to an on-the-fly calculation.

Several challenges in the design and construction of this system can be foreseen. In order to construct the physical system, it will be necessary to machine several metal parts. A method of keeping the ball on the plate rolling when in motion rather than sliding is also necessary. A rubber membrane is on order to cover the touch pad with a frictional surface. However, the thickness of this membrane will also affect the sensitivity of the touch pad and therefore the necessary mass of the steel ball will need to be large, mandating a ball of large proportions.

Gathering position data from the touch pad will also provide an added challenge. A serial interface controller is included with the kit, however additional precision is needed for our application, so we will have the added chore of developing a system to drive and sample the touch pad in order to generate the X-Y coordinates required.

Finally, the control problem itself will be a significant challenge. Currently we intend to design the system as two uncoupled links, yet there may in truth be greater than negligible nonlinearities and coupling effects between the links. In addition, designing the system using

The project is split up into three main subsystems: the data acquisition system, the motor controller system, and the dynamic modeling of the motors. Each of these subsystems has its own objectives and goals in order to make the entire project work, however they do not act independent of one another. For purposes of analyzing the system as a whole, it was much easier to split up the tasks into three sub-categories.

The goal of the data acquisition system is to obtain the signal from the transmitter in order to successfully locate the object in a smooth and continuous pattern. However, as in any design, there are many obstacles that will hinder the ultimate success of this project. The first problem that will cause delay is the fact that the system will not be fast enough to continuously update and therefore will have a very choppy path instead of a smooth one. For the DAS side alone, there are many layers of calculations and steps that must be done quickly enough for the camera to constantly follow the object. If any one of these steps or subparts fails, the whole system will crash. Other challenges that may cause delay with the completion of this project are improper circuitry production, improper implementation of the different parts, and basic calculation errors that might need extra debugging. The original scope of this project was to have a working vision tracking system to follow a football during a game. However, due to our limited resources and space availability, the constraints mentioned in the introduction needed to be implemented.

This project will enable a camera to visually maintain an RF transmitter as its center of
a full state-feedback control system or a linear-quadratic state-feedback regulator (LQR) will be far more complicated than simple PID control. In order for this to be accomplished, the predicted motions of the object must be taken in order to allow the camera to move ahead of the object itself so that it meets the object when it arrives at the next time step. By using this predictive positioning method, the motions of the tracking system may be constrained to smooth motion at each adjustment. The point of this is to allow the viewer the cleanest possible perspective of the object and its surroundings.

The motor controller subsystem is the final system of the project. It dictates where the camera focuses, based on the inputs from the data acquisition subsystem and the specifications from the dynamic system model. The main goal of this system is to move each of the motors to the desired angles at any given time while the program is running so that the object will always remain in the scope of the camera. In order to accomplish this task, an acceptable controller must be created for each motor, and the data from these controllers must be properly passed from the program to the motors.

**Design Strategy**

**3.1 Model Development**

Due to the complexity of this system, a highly accurate, non-linear model must be developed. In order to consider a Lagrange-Euler dynamic model, the kinetic and potential energies of the system must be found. The kinetic energy is comprised of the energy due to both the linear and angular motion of the system, and can be represented as an inertia tensor. Gravity, friction, and velocity coupling terms must also be considered to represent the full non-linear dynamic model.

Professor Wen’s pantilt.m script was used to define the symbolic equations of motion for our system. In this file, the gravity vector had to be changed to point in the negative-X direction to account for our system’s vision.

**DATA ACQUISITION**

The data acquisition system is being developed solely on MatLab before any hardware is built, to verify that MatLab can ultimately accomplish what needs to be done for the camera to follow the object at a smooth, fast, and accurate pace. The next step after the necessary MatLab functions are written and completed is to implement the hardware to give us the real data.

A/D Converters – 0 to 255
Filter out Sporadic numbers and zeros
1. Transmitter to Signal
orientation change. This script returned symbolic values for the inertia tensor, velocity coupling matrix, gravity loading vector, and total energy. As expected, the gravity loading vector contained a term for the pan axis due to our orientation.

Based on a Solidworks model of our system, the inertia tensors for bodies A and B with respect to the defined output coordinate systems as shown in Figures B and C were found to be:

\[
I_a = \begin{bmatrix}
2.4 & 0.0123 & 0.0004 \\
0.004 & 0.0092 & 0.0009 \\
0.004 & 0.0009 & 0.0353
\end{bmatrix}
\]

\[
I_b = \begin{bmatrix}
2.4 & 0.021 & 0 \\
0 & 0.0005 & 0 \\
0 & 0 & 0.0025
\end{bmatrix}
\]

(3.1)

Solidworks also provided the total mass of the bodies. Since the equations of motion were left in symbolic form, values for inertia, mass, and other parameters can be easily changed.

In addition to these equations of motion for bodies for bodies A and B, a model must be developed for the ball itself, body C. In Professor Craig’s previous work in the Mechatronics department here at RPI, equations of motion for the ball based on the platform angles were developed. Based on the small angle assumption made, Eqs. (3) and (4) in [3], should hold true for our system. This provides us with equations of motion for the ball in non-linear form. For now, the non-linear model will be considered, however Professor Craig’s system was linearized to decouple the two modes of motion. See Eq. (5) in [3]. The inertia of the ball was found for the equation of inertia for a solid sphere[5].

\[
I_c = \frac{2}{5} mc^2
\]

3.2 Performance Specifications vs. Available Components

Beginning with the physical specifications of the desired system, quickly we see that we require several simple parts that are unavailable from the set of components with which we have been provided. In order to construct the system, several metal parts need to be machined in order to accommodate the 10.4 inch touch-screen platform. These parts include a new yoke, motor mount plate, and specialized shaft. The yoke and mount plate are much larger than those originally provided, and material has been removed from a larger diameter shaft in order to position the platform at the center of the axis of rotation. The overall

Strength Meters
Determine XYZ coordinates (in feet)
Compare to previous position for validity and feasibility

This is the design flow chart for the DAS design side of this project. It will eventually be implemented with the control system, which will complete the design. See Appendix A for the simulink files which will filter sporadic and unwanted signals as well as output a vector (in feet) of the placement of the transmitter.

The system may be divided into two main subsystems. The data acquisition system (DAS) will consist of the sensors, transmitter, and predictive positioning of the transmitter at the next time step. The only outputs from this system will be the x, y, z coordinates at time step +1 (t+1). The controller system will take as input the predicted x, y, z coordinates of the object and the current state of the encoders and from this will derive the new orientation of the camera. From this orientation the motors shall be fed a current in order to reposition the camera.

The integral part of the DAS is the signal strength meters that will be used to determine the location transmitter and thus, the object. The circuit of each signal strength meter is as follows. Figure 2

The two capacitors labeled C3 and C5 are used to steady the voltage as it flows in from the 9 volt power supply, so that extreme highs or lows that could be damaging to the op-amp never reach the amp. Of the two op-amps which are used in the meter, the first is used as buffer to keep the impedance constant to couple high impedance to low impedance. A 1K ohm potentiometer is also included so the signal strength meter can be balanced to zero when it isn’t measuring any signals. The output voltage is measured across a diode which is used as a voltage rectifier. The most important part of the circuit is the filter, which the RF signal runs into immediately after it is received. The filter is used to eliminate unwanted noise which characteristically travels through the air and
weight of the final system will be approximately 1.2 kg. These parts can all be seen in the cad model in Figure D.

would normally affect the RF signal. This filter consists of a tank circuit in conjunction with an op-amp. The tank circuit is used to set the frequency range at which the signal strength meter will be active, while the op-amp is used to amplify signals which stand out in the frequency range. (1, 3, 4)

4.1 Testing Procedure

Though little testing will be necessary for the newly machined parts, it should be noted that they must be accurately made. It is especially important that the axle be straight and the holes in the yoke be of the proper size and exact placement in the yoke so that the platform will properly spin about the tilt axis. This can be tested by simple measurement and observation. The test of the motors’ ability to perform their task will be quite simply whether they are able to rotate this heavy system at the speeds desired in order to control the ball. This will be testable with a Simulink/MATLAB setup. Various inputs and the resulting position graphs read from the encoder can easily be used to test the limits of the motor’s ability.