A SYSTEM FOR SUPPORTING TEACHING MODERN CONTROL SYSTEMS AT UNDERGRADUATE LEVEL

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Abstract— In this paper a teaching platform used to track a moving target object with a camera mounted on a turret located on a moving platform is presented. In this system, a platform with six degrees of freedom was used to simulate a moving vehicle. A digital camera was placed on a turret and mounted on the platform to simulate a sensor mounted on a vehicle turret. The camera's onboard software identified the location of the center of mass of a target object within its field of view. The objective for the students is to develop a linearized model of the turret movement and design controllers for the azimuth (pan) and elevation (tilt) of the turret in order to keep the target object at the center of the camera's field of view. A working solution proposed by students during their final project is presented. A controller developed using Model Predictive Control (MPC) was able to adjust for both the movement of the target object and the unknown disturbances introduced by the motion of the platform carrying the turret. This system can be used to teach different control techniques allowing for easy implementation and test of students' solutions.

Keywords— Control Systems Lab, Engineering Education.

1 Introduction

In order to implement an effective control system, students need to master a variety of topics such as sensing, instrumentation and measurement, signal processing, system modeling, the design of the controller itself and performance evaluation; while mastering several mathematical topics not generally needed (or needed with a different focus) in other engineering disciplines (Braatz, 2013). For these reasons, usually control systems have been taught at senior undergraduate courses or in several iterative courses starting with the mathematical background until students can develop physical intuitions of the systems being controlled. Often students never actually work with physical systems other than very simple DC motors.

It has become more evident in recent years that a new approach to teach key concepts of control systems is necessary. Among the techniques that have been recently tried, one may cite: interactive course material (Hassapis, 2003), the use of robots (Sanchez and Bucio, 2012), the use of interactive visualization tools (Guzman et al., 2016) and hands-on approaches (Baglione and del Cerro, 2014). However, most of the systems are focused on either graduate level teaching or only classical techniques such as PID design. This paper describes a complete system that allows students to deal with several key problems in control systems design (the above mentioned sensing, signal processing, etc.). In the proposed system, all these tasks are executed by students using state-of-the-art tools while focusing in modern control techniques such as model predictive and adaptive control as well as the classical PID design.

The teaching platform presented has been designed in-house using off-the-shelf components developed by Quanser Inc. The system mimics a vehicle carrying a camera as, for instance, a quadrotor Unmanned Aerial Vehicle (UAV). As an example, a UAV may be required to carry a camera to track a moving target, such as in sports events (tracking a football, for example) or search and rescue operations. Furthermore, if a free-space data channel is available, stabilization of a gimbal may be necessary (Harris et al., 2005).

The first problem, sensing, is obviously sensor specific. The platform described in this paper uses a camera for measuring the position of the external object as has been studied by others (Papnikolopoulos et al., 1993). The sensor used in the teaching platform is a Firefly MV camera (Grey, n.d.) produced by Point Grey Research Inc. Furthermore, the camera is used with the FlyCapture SDK software providing the target object detection. As part of the design task, students must evaluate the quality of the measurements and define metrics for assessment. Part of the signal processing necessary is implemented in MATLAB, but the camera itself already has certain filters that students may use.

The main task in the system is, therefore, the control of the turret located on the moving platform, which mimics the behaviour of a vehicle, autonomous or not, in order to keep the sensor on target. As the system used a turret mounted on a moving platform to hold the camera, this meant that there are three separate moving components of the system: the target object; the turret and the moving platform. In order to represent an arbitrary real world application, the system has no model of the motion of the target object. This requires that the control algorithm employed be as robust as possible (Li and Jilkov, 2003). For the system modeling task, students must find a linearized approximation of the motion of the turret, from first principles (in a first encounter with control systems) and then through an identification algorithm (in a senior class). The motion of the platform itself is left as unknown disturbances to the system.

When choosing a control algorithm several factors must be considered by the students including: that the movements of the turret need to be constrained in both rate and maximum distance; there are non-linearities in the system motion that need to be compensated for; and that the target movement adds uncertainties to the system. Students then suggest approaches to deal with the problems such as LQG and Kalman filters (even though they not seem to be well suited for this application (Qin and Badgwell, 2002)).

For each possible implementation of the system, students will change some blocks or omit existing ones or add new ones, depending on the constrains of the design. Section 2 describes all the equipment used in the development of the system and details how the teaching platform is setup. In section 3, the problem in which the students work is described in detail, including the control problem, the linearization of the turret sub-system and the identification of the system. Section 4 describes an actual exercise performed by students of the fourth year of an Electrical Engineering degree. It includes the design chosen and explains the evaluation criteria used as well as the experimental results achieved. Finally conclusions are stated in section 5.

2 System Description

As stated before, the system was developed in order to emulate a moving platform with a turret. In order to achieve the realistic motion of a vehicle, motion in six dimensions; the three spacial dimensions, x, y and z and the three Euler angles, roll (ϕ), pitch (θ) and yaw (ψ); needs to be provided. This is accomplished through a hexapod platform (Figure 1) that is electrically actuated. Any motion can be sent to the platform from a personal computer (PC) running Matlab/Simulink models through an amplifier plugged onto a data acquisition board. The hexapod is an off-the-shelf piece of equipment that is used for simulating vehicles (motion over rough terrain) and earthquakes as well as for performing stress tests.

The objective of the solution proposed by students is to keep a sensor (in this case a camera) fixed on a target. A customized turret (Figure 2) with two motors was used as the device to accomplish the tracking. Again, one can actuate the turret's pan (ξ) and tilt (υ) via the PC and a

Figure 1: 6 DOF platform used for system disturbances.

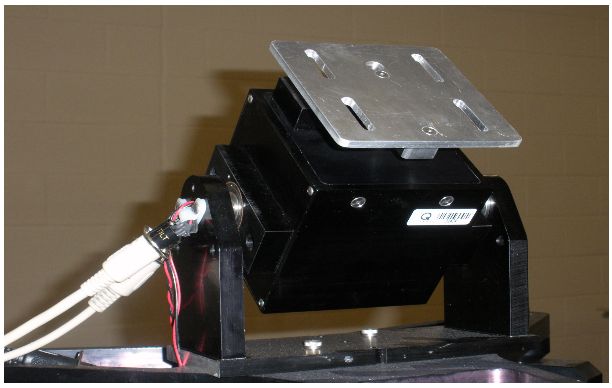

Figure 2: Turret to be moved to track in pan and tilt.

Matlab/Simulink model running in real-time. The motors are regular DC motors actuated via PWM signals.

Finally, the target object (target) is mounted on a linear motion device that only moves horizontally in front of the turret, as seen in Figure 3. The linear motion device is $2.10m$ long and the target can move at a maximum speed of approximately $5080mm/sec$.

The block diagram for all the components of the system can be seen in Figure 4. This figure includes one possible control solution that will be discussed in the next two sections as a case study for illustration.

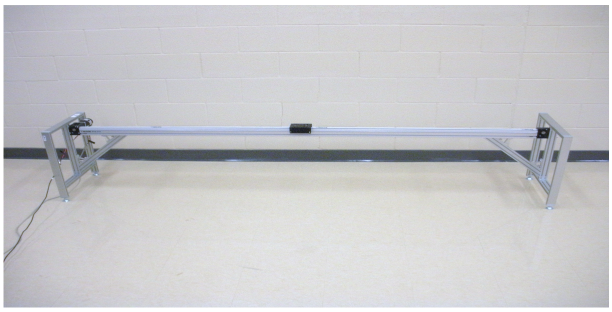

Figure 3: Linear motion device to move an object in the x-plane.

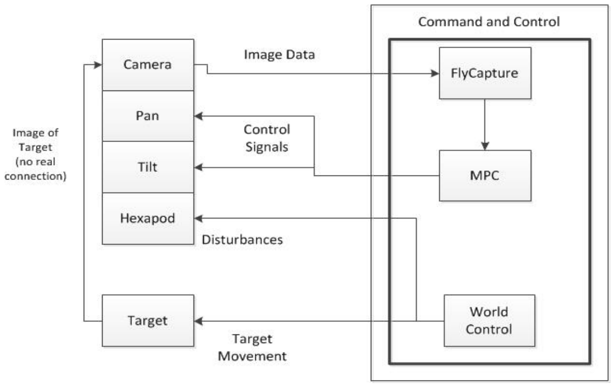

Figure 4: Target Track Block Diagram.

3 Problem Description

In a nutshell, the problem in which the students work is that of self-correcting tracking of an object of unknown position and velocity using an independent system consisting of a 2 degree-of-freedom (DOF) pan and tilt turret mounted on a 6 DOF platform that simulates a moving vehicle platform. The next subsections describe in more details the target, the vehicle and the turret, further explaining Fig. 4.

3.1 Vehicle Platform

The vehicle platform is known as a "hexapod" and it allows motion in six dimensions, the three axes x,y and z, and the three Euler angles. The motion may be thought of an unknown disturbance that simulates the motion of a vehicle over rough terrain. The motion of the vehicle platform is controlled by a Simulink model unknown to the control system. The motion used may represent the motion of an air vehicle (high-frequency motion), a ground robot (rough terrain variations) or a surface water vehicle (waves in different sea conditions).

3.2 Target

The target system is composed of a linear bar, a DC motor and a platform where the target itself is mounted. The motor is controlled through another Simulink model that is also unknown to the control system. In the implementation, the target maintains horizontal motion as a random combination of sinusoidal signals. The target used by the students is an airplane printed in a 3D printer and painted in a single color.

3.3 Turret

As discussed previously, the turret is located on top of the vehicle platform that moves in all three axes x,y and z, and the three Euler angles. Furthermore, the motion of the vehicle platform is unknown and is considered as disturbance for the turret.

In order to properly track a moving object with this turret setup the target must be identified relative to the pan and tilt position of the turret. Target identification will be established through a camera on the turret monitoring the target location based on pixels. The turret position, in pan (ξ) and tilt (υ), then needs to be adjusted to maintain a visual on the target. This will be discussed more in the experimental results section. The distance to the target (Z-plane) is not considered for this design as the camera used to identify the target has only a two dimensional field of vision and this is not necessary for tracking to take place.

3.4 Modeling

The pan and tilt motions are the dynamics used in the design of the controller. These motions are nonlinear in nature and, in order for a linear controller to be implemented, linear approximations of the two motions are required.

Students are instructed to derive second order system transfer functions

$$X = \frac{k{\omega_n}^2}{s^2 + 2\zeta\omega_n s + {\omega_n}^2}\, X_d \qquad (1)$$

where X_d is the desired pan/tilt, X is the current pan/tilt positions, ω_n is the natural frequency, ζ is the damping factor and k is a constant.

They may choose to work with an approach that requires the state space representation for the pan and tilt in (2) through (3).

$$\begin{bmatrix} \ddot{X} \\ \dot{X} \end{bmatrix} = \begin{bmatrix} -2\zeta_1\omega_{n_1} & -{\omega_{n_1}}^2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{X} \\ X \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} X_d \qquad (2)$$

$$Y = \begin{bmatrix} 0 & k_1{\omega_{n_1}}^2 \end{bmatrix} \begin{bmatrix} \dot{X} \\ X \end{bmatrix} \qquad (3)$$

where X is replaced by ξ and υ with the appropriate k, ζ and ω_n (the gain, damping ratio and natural frequencies) for each case; and Y is the output. Notice that both systems for ξ and υ may be combined in only one.

3.5 System Identification

In order to find the parameters of the equations presented in section 3.4, students may derive the system from first principles or use a system identification approach. If using first principles, the students need to estimate the masses and moments of inertia of the components. To that avail, they are provided with tools for measurement.

In the undergraduate courses already in the curricula, students cover Least-squares and this becomes their main method of choice. They need then to choose the type of signal they will use for the identification (step, square, sinusoidal, etc.), the frequency of the signal, if required, and the number of data points. Students may also derive a first order model for comparison.

4 Case Study

In this section we will discuss a possible solution based on Model Predictive Control (MPC) for the system proposed by students of a fourth year control course. The solution is based on content covered during their undergraduate degree. Notice that other methods (such as Adaptive Control) could also be used. However, they will not be presented in this paper.

Section 4.1 describes the concepts that the exercise is intended to clarify as well as how the work is evaluated throughout the course. Section 4.2 describes the control design. Section 4.3 shows the results achieved by the present case study. Finally, section 4.4 quickly reports on the feedback received from the students involved.

4.1 Evaluation Criteria

The objective of the fourth year Control Systems course is to introduce modern control techniques such as Model Predictive Control, Adaptive Control as well as correlated topics such as system identification and Observer design.

Interfaces with the sensors (camera and potentiometers) are provided, but filtering of the raw data is not. However, a library of filters is provided and students may choose the applicable ones. Also, the connection with the platforms (vehicle, target and turret) are provided and the students can only see and modify the turret module.

Students are required to elicit requirements in an initial proposal. Then, at each milestone, the requirements need to be updated. Requirements' management counts for 20% of the mark for the project. Marks were awarded for clarity of requirements, good management practices and fulfillment of requirements in the final product.

The design proposed by the students is marked base on their technical merits (if the design is properly done), feasibility of the approach and quality of implementation. The design counts for 50% of the marks.

Finally, results count for 30% of the marks, which are spread based on the choice of good metrics demonstrating the fulfillment of requirements, the quality of the results compared to the requirements and the technical description of system performance with the use of figures, graphs, tables and text.

4.2 Control Design

Students started the project by defining requirements for their controller. The criteria chosen was based on the Root Mean Square (RMS) error of tracking. The platform was chosen to simulate a boat on conditions of sea state 5 (rough) and 6 (very rough) (White and Hanson, 2000).

The students chose MPC due to the fact that the method is able to handle a multivariable system with ease (Camacho and Bordons, 2007). Therefore, both control modes may be combined in only one controller design. As such, the controller is able to handle both calculations simultaneously with no detectable adverse effects.

The quadratic optimization objective of the MPC is handled via the minimization of the associated cost function according to the weights of the outputs, inputs and input rates. As described in (Iskandarani et al., 2013) the cost function can be

$$J(\bar{x}, \bar{u}, \Delta u) = \sum_{i=0}^{p-1} \Gamma^T Q \Gamma + \Delta u(k{+}i|k)^T R_{\Delta u} \Delta u(k{+}i|k) + \bar{u}(k{+}i|k)^T R_u \bar{u}(k{+}i|k) \tag{4}$$

The components of the cost function are:

$$\Gamma = \bar{x}(k+i+1|k) - r(k+i+1|k) \tag{5}$$

where p is the prediction horizon, $\bar{x}(k) = [\Xi \;\; \Upsilon]^T$ is the output vector that contains the current states of pan and tilt angles and $\bar{x}(k+i+1|k)$ are the predicted outputs for time $k+i+1$ at time k. Also $r(k+i+1|k)$ is the reference for time $k+i+1$ at time k. The reference comes from the sensor tracking the target, in this case the camera. The inputs to the system, or the manipulated variables, are $\bar{u}(k) = [\xi_d \;\; \upsilon_d]^T$ and $\bar{u}(k+i|k)$ is the manipulated variable for time $k+i$ at time k. $\Delta u(k+i|k)$ is the manipulated rate variable for time $k+i$ at time k. Q, $R_{\Delta u}$ and R_u are positive semi-definite matrices that have the weights for the output, manipulated rate and manipulated variables respectively.

Furthermore, the time period for the controller is set to 0.001 seconds providing updated control signals in real time. The rapid adjustments of control signals allows for very quick and accurate response time for the object tracking. Due to the speed at which the optimization of the cost function is being performed, certain constraints are implemented in the LMPC design. The output vector $\bar{x}$, the manipulated variable rate $\Delta\bar{u}$, and the manipulated variable $\bar{u}$ are subjected to the constraints in (6)-(10). The same values are used for pan and tilt.

$$-1.5rads \leq \Xi \leq 1.5rads \quad (6)$$
$$-1.5rads \leq \Upsilon \leq 1.5rads \quad (7)$$
$$-0.75rads \leq \xi_d \leq 0.75rads \quad (8)$$
$$-0.75rads \leq \upsilon_d \leq 0.75rads \quad (9)$$
$$-1.5 \leq \Delta u(t) \leq 1.5 \quad (10)$$

These constraints ensure that the system tracks at a stable rate and minimizes jitter and overshoot. The output variables are limited according to (6) and (7) such that safety of the system is achieved by not allowing the system to go out of its normal bounds.

The prediction and control horizons were carefully chosen in order to achieve a good balance between increased system response, stability and the computational effort required for the cost function minimization, as one of the primary goals was to have the system executing in real-time. The chosen values were a prediction horizon $p = 9$ and a control horizon $m = 7$.

4.3 Results

The main objective of the experimental tests are to prove that the designed controller can provide accurate tracking in both the horizontal and vertical planes under a variety of different target and vehicle motions and speeds. The criteria for accurate target tracking is broken down into a target pixel area and can be seen in Fig. 5. The root mean square (RMS) data presented in Fig. 6 represents the average radius from the center of the camera's field of view in pixels. The colours of the boxes of Fig. 5 correspond to the locations of the coloured RMS values in Fig. 6.

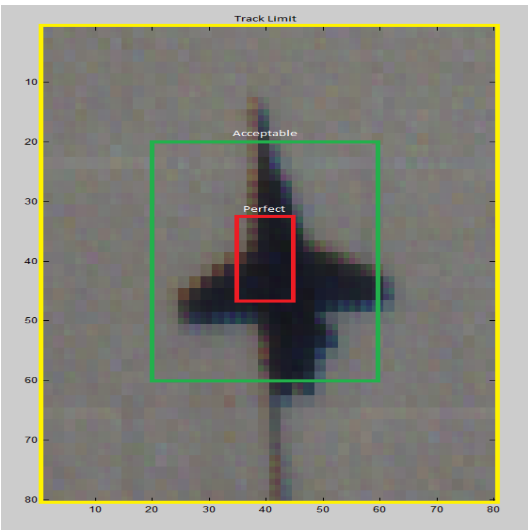

Figure 5: Acceptable Target Tracking Areas

A variety of tests at different amplitudes and frequencies were run in order to get an accurate

		No Platform Motion, Target Movement			Platform Motion, No Target Movement			Platform Motion, Target Movement	
Test Function	Duration	Pan	Tilt	Duration	Pan	Tilt	Duration	Pan	Tilt
100mm Step	18	4.34	8.45				33	5.95	15.35
-100mm Step	19	4.44	8.42				31	5.98	12.55
200mm Step	22	5.98	9.26				41	6.85	11.78
-200mm Step	39	5.38	11.99				54	5.29	14.24
4 X 100mm Step	33	4.73	7.71				0		
Sine 0.25Hz, 100mm	68	5.47	10.58	52	3.87	8.77	57	6.47	15.11
Sine 0.25Hz, 300mm	68	9.64	10.30	59	3.05	8.78	70	10.39	14.71
Sine 0.25Hz, 500mm	75	14.18	10.34	62	15.50	19.60	65	12.64	14.09
Sine 0.35Hz, 100mm	56	5.97	10.88	49	3.45	8.67	63	6.75	18.82
Sine 0.35Hz, 300mm	67	10.94	11.22	53	3.80	10.77	86	11.24	15.78
Sine 0.35Hz, 500mm	75	15.64	10.36	51	10.28	20.53	60	18.46	21.86
Sine 0.50Hz, 100mm	62	8.32	10.28	55	3.27	8.63	67	7.39	12.00
Sine 0.50Hz, 300mm	75	14.19	10.70	61	8.51	17.35	62	12.22	14.93
Sine 0.50Hz, 500mm	75	20.50	12.22	107	15.27	24.34	86	19.05	23.57
Sine 0.65Hz, 100mm	73	12.89	11.79	71	2.71	8.09	54	10.73	12.87
Sine 0.65Hz, 300mm	75	22.46	14.09	60	12.25	22.49	74	20.78	21.63
Sine 0.65Hz, 500mm	76	28.70	27.79						
Sine 0.75Hz, 100mm	75	18.44	13.33	51	3.59	9.43			
Sine 0.75Hz, 300mm	75	28.47	27.86						

Figure 6: Root Mean Square Experimental Results for Target Tracking in Different Scenarios

overall assessment of the tracking RMS error as shown in Fig. 6. As it would be expected, the results became less and less accurate as the amplitude and or frequency increased; however, tracking was never lost, the system was able to track the target and the sensor always had the target in view. As a baseline graphical representation of the results the data at amplitude 100mm at 0.5 Hz can be seen in Fig. 7. The results have been normalized with respect to the targets size and it can be seen that the turret is always tracking within the size of the target. Therefore, the task of tracking a target accurately, as based on the above discussed criteria, in both the horizontal and vertical planes was accomplished successfully.

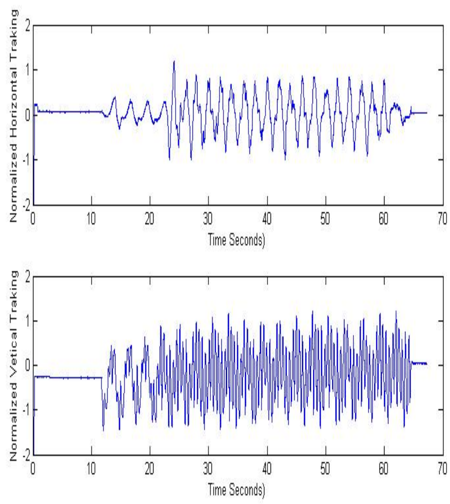

Figure 7: Pan and Tilt Root Mean Square Normalized to Target Size Experimental Results at an Amplitude of 100mm and Frequency of 0.5Hz

4.4 Students Assessment

Students that worked on this project were very satisfied with the approach. They stated that the use of a concrete platform (instead of a “toy” application) was motivating. They also liked the fact that they could apply the knowledge they acquired in the classroom to an engineering problem. However, students enrolled on a voluntary basis. In the near future, we intend to run a full course with the aid of the platform in order to assess the efficacy of the teaching platform.

5 Conclusion

A teaching platform that simulates a turret on a moving vehicle intended for control systems education was developed. The system is assembled with off-the-shelf components and it can be used for an introductory or senior level control course. Key concepts can be studied and easily implemented. Students work on sensing, signal processing, modeling, identification, control and validation in a concrete problem.

In order to ease the teaching environment, a library of filters for the camera is available for the students. However, students have to still choose the appropriate filters for their work. Modeling is either explicitly done (from first principles) or system identification may be used. The controller can take several forms, depending on the motion of the platform, which may emulate a ground, air or surface water vehicle.

A pilot case study was presented and the students succeeded in implementing a control solution for the problem during a term of study. Results show that the control solution was successful and appropriate. Feedback from the students was positive and key concepts of control systems were presented in a concrete way.

In the future, we intend to use the developed platform to both an introductory and also a senior level control systems course. We then intend to assess the students’ feedback in a more representative way. Nevertheless, initial assessments suggest that students are in general satisfied and motivated by a hands-on-approach of a concrete control systems application.

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