Trajectory Following With the Tower Crane

Advanced Controls Lab 5 - 10/30/17

***Abstract*—The driving force behind this competitive experiment is to highlight the challenges faced when designing suitable control techniques for maneuvering a pendulum hook and payload system through an obstacle course from start to end positions. Accurate trajectory control for such a dual-mode system is made difficult by the presence of unknown states such as the payload angle of oscillation relative to the hook. While this can make it extremely difficult to apply model-based control methods such as model reference control, a model-free approach like input shaping of the command velocity is extremely effective in ensuring stable operation of the double-pendulum crane.**

I. Analysis of System Dynamics

THE first manipulation task involved operating the crane with no shaping applied to the slew, trolley (radial) and motorized spool (hoist) velocity inputs. Avoiding residual oscillations of this pendulum system was simply left to the operators dexterity. We can see greater levels of tangential deflection in this case (see Fig 1), which is expected since the crane is slewing the majority of the time, and the operator makes errors in maneuvering the crane like stopping too fast. The next manipulation task was made simpler by choosing a single input shaper that would provide robust performance during both the first half of the trajectory (single pendulum case) and the second half which involved picking up and moving the payload (double pendulum case). Figure 1 clearly shows a reduced tangential deflection compared to both the unshaped and autonomous runs. The final manipulation task was programming a trajectory for the crane to follow autonomously, while still fulfilling the necessary requirements of navigating to the payload, picking it up and dropping it off in the final location. Since the task was automated, it is also the fastest to finish the maneuver to the end goal (indicated by the point where deflection drops to zero). Using different specialized shapers for the single mode and double mode parts however, seems to have slightly increased the overall oscillatory behavior.

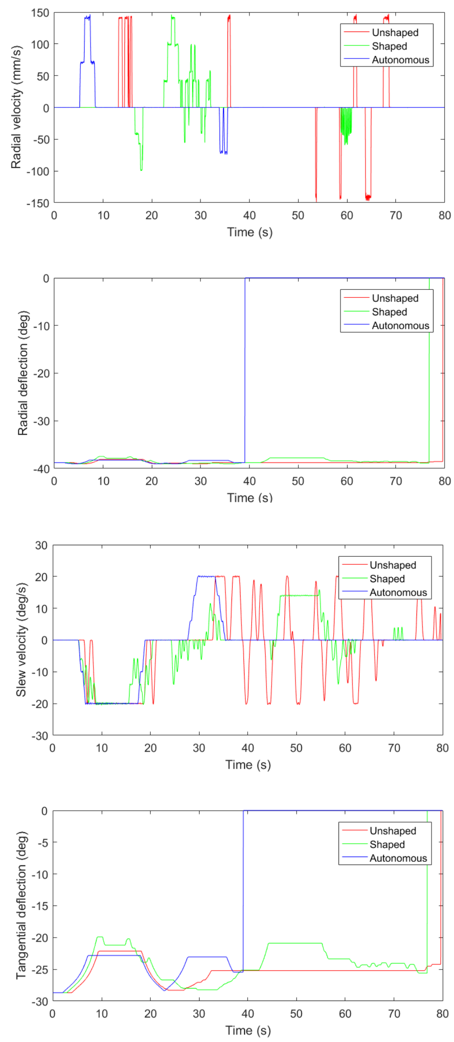

Fig. 1. Plots showing input velocities to the trolley (radial) and crane (radial) and their effect on the systems oscillatory behavior

II. Input Shaper Design

Several input shapers were considered for the lab assignment. The most promising were a two-mode ZV shaper and two different EI shapers. The two-mode ZV shaper was designed around the two natural frequencies of the double pendulum, while both EI shapers were designed around the average of the two natural frequencies. The assumed length of the first pendulum was 0.820 m and the given length of the second was 0.7 m, making the two natural frequencies 2.93 rad/s and 5.10 rad/s, and the average 4.02 rad/s. The operation time of the EI shapers were slightly faster than the operation time of the two-mode ZV shaper by about 0.124 seconds. One EI shaper was designed around a tolerable vibration of 5 percent. The second EI shaper was designed by iterating through different values for the tolerable vibration until the magnitude of residual vibration at the two double pendulum natural frequencies became zero. The resulting value for tolerable vibration was 20.53 percent. While it does have a slight time advantage over the two mode ZV shaper, it is also slightly less robust, but it was the shaper ultimately chosen based on the easy to predict machine response time for the operator. Sensitivity curves are shown in Figure 2.

Several single mode shapers were tested with frequencies corresponding to the single pendulum length at the start, each mode of the single pendulum, and the average frequency of the

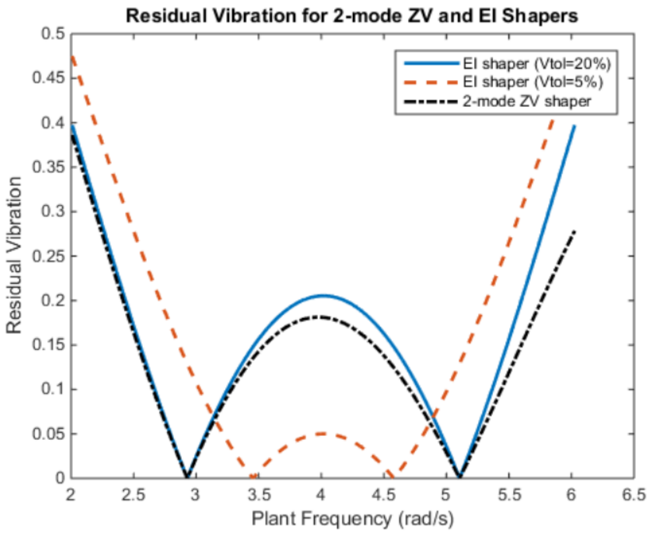

Fig. 2. Residual vibration of EI shapers and two-mode ZV shaper

double pendulum modes. All of the single mode ZV shapers were found to be too difficult to control the payload with confidence.

III. Autonomous Trajectory Design

To create a preprogrammed tower crane trajectory, slew, trolley, and hoist way-points were first measured at different locations along the desired trajectory: this included the crane start location, the hoist and trolley positions required for obstacle clearance throughout the trajectory, the payload pickup location, the positions required for payload pickup and movement, and the payload drop-off location. Using these way-points and the maximum velocity and acceleration limits for each crane axis, acceleration commands were created for movement between each way-point. Each set of acceleration commands required to reach the next way-point were calculated to begin with the end of the previous set of velocity commands. The acceleration commands were then integrated twice to produce the corresponding velocity commands and the theoretical crane trajectory, as shown in Figures 3,4 and 5.

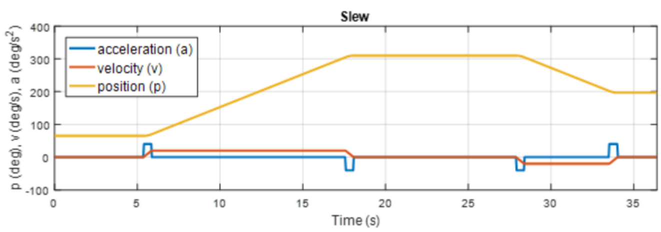

Fig. 3. Tower crane slew position, velocity, and acceleration for unshaped preprogrammed trajectory.

Shaping was added to slew and trolley velocity commands, based on hoist height. For the initial move from the start location to the payload pickup location, a single-mode ZV

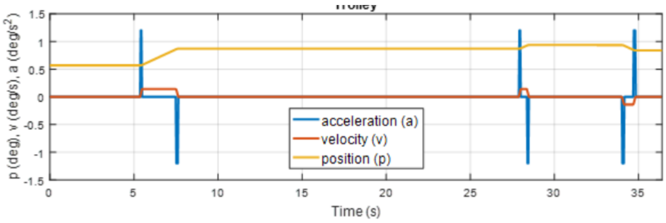

Fig. 4. Tower crane trolley position, velocity, and acceleration for unshaped preprogrammed trajectory.

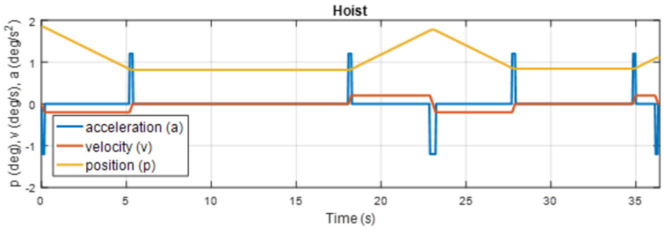

Fig. 5. Tower crane hoist position, velocity, and acceleration for unshaped preprogrammed trajectory.

shaper with a period matching that of the crane was used. For the move from the payload pickup location to the goal location, an EI shaper with a period based on the average of the double pendulum frequencies was used. Subsequently, velocity command sets were overlapped based on crane testing to reduce the trajectory time. For example, the slew and trolley move commands to move the crane from the start location to the payload location before the initial command to move the hoist up ended. Initially, the trajectory was optimized for time only; however, more oscillations were introduced by overlapping slew and trolley commands with hoist commands. Therefore, to better ensure the crane would place the payload into the cup by minimizing payload oscillations, command overlap was reduced. The shaped and time-shifted velocity commands are compared to the original unshaped and time-shifted velocity commands in Figures 6 and 7.

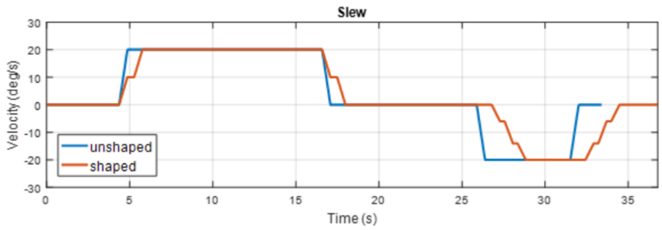

Fig. 6. Comparison of unshaped and shaped tower crane slew velocities for preprogrammed trajectory.

For implementation on the tower crane, the velocity commands for the desired trajectory were discretized to match the 40-millisecond crane controller frequency. Three tests were run prior to the contest to verify the trajectory performance and for all three tests, the payload was successfully picked up and deposited in the cup at the goal

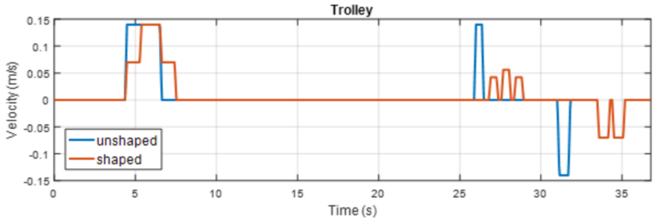

Fig. 7. Comparison of unshaped and shaped tower crane trolley velocities for preprogrammed trajectory.

location without contacting any obstacles. However, for the competition trial, the payload was not successfully placed in the cup (although no obstacles were hit). Any variation in the payload and magnet position prior to pick-up by the crane impacts the oscillation behavior of the crane once the payload is picked up. Therefore, even a small difference in initial payload positioning may produce enough oscillation that the payload will miss the cup. An alternative to mitigate this issue would be to add a time delay after the crane moves to the cup location before the payload is deposited to allow for damping of oscillations.

IV. Contest Results

Our recorded times for each of the competition categories can be summarized as follows:
1. Manual Operation Without Input Shaping.
a. Local 57.2 secs
b. Remote 45.7 secs
2. Manual Operation With Input Shaping.
a. Local - 2 mins 44.2 secs
b. Remote - 1 min 35.1 secs
3. Pre-Programmed Trajectory - 35 secs (not successful in dropping payload to cup)

V. Optional analysis of a model reference control implementation

While completely unnecessary for accomplishing the goals of this lab, we also decided to look into the difficult task of implementing a model reference control method for vibrational reduction in the double pendulum tower crane system, simply out of curiosity. The first task was finding the transfer function of a fourth-order SISO plant that would represent the actual double pendulum, by adding the two second order systems corresponding to each of the two pendulums. Since the input to this system is the velocity command and the output is the angular deflection of the payload (which cannot be measured but only estimated), a recursive least squares approach was used to estimate the unknown coefficients of the plants transfer function. The resultant SISO plant has a Z-domain transfer function as shown in Figure 8

```
  0.03811 z^3 + 0.001888 z^2 - 6.691e-05 z + 4.37e-06
  ----------------------------------------------------------
z^4 - 0.001524 z^3 - 7.551e-05 z^2 + 2.676e-06 z - 1.748e-07

Sample time: 0.04 seconds
Discrete-time transfer function.
```

Fig. 8. Plant transfer function.

Since directly converting this z-domain representation to its corresponding difference equation in state space form is not possible due to the system being causal, a controllable canonical state-space realization was derived by setting W(z)=(Input signal u)/Denominator of Plant Transfer Function. The four resultant states were thus: x1(k)=w(k) , x2(k)=w(k+1), x3(k)=w(k+2) , x4(k)=w(k+3) And the coefficient matrices obtained are shown in Figure 9:

```
G =
        0    1.0000         0         0
        0         0    1.0000         0
        0         0         0    1.0000
   0.0000   -0.0000    0.0001    0.0015

H =
   0
   0
   0
   1

C =
   0.0000   -0.0001    0.0019    0.0381

D =
   0
```

Fig. 9. Plant coefficient matrices.

A similar state space representation was obtained for our model, which was approximated using a zero damping assumption, combining individual pendulum 2nd order systems in the continuous domain, discretizing it with the cranes sample time of 40ms and finding the controllable canonical state-space representation. Lyapunovs direct method was then used to solve for the positive definite, symmetric and real P by choosing a 4x4 identity matrix as the Q matrix. Then, using the resultant P matrix in the equation for M=0, the control law u can be summarized as follows:
u = v - x1 + 3.9*x2 - 5.9*x3 + 3.9*x4
Whether this control law is able to suppress the dual mode oscillations or can even be implemented in the actual crane system without exceeding the actuator limits is a question that remains unanswered.

References

[1] W. Singhose and W. Seering *Command Generation for Dynamic Systems*. William Singhose, August 17, 2011.