ME 6404: Advanced Control System Design and Implementation
Lab 5: Trajectory Planning

Max May, Yuen Bak Ching, Fabia Bayer

Abstract: The fifth laboratory task is a summary of all that was taught in the class ME 6404. The objective is to use a tower crane to move a payload through an obstacle course and deposit it at the right place with five different operation modes ranging between distant manual operation and an automated trajectory. Methods like Input Shaping, Model Reference Control and Zero Phase Error Tracking Control can be used to accomplish this task. In this report, approaches for manual shaped operation and automated trajectories are discussed and the performance is evaluated.

1. MODELING AND SYSTEM DYNAMICS

1.1 Obstacle Course Setup

The obstacle course consists of three main stages. The crane starts at the starting position. It then turns an angle of approximately 280 ° and drives inward for 261 mm to pick up the payload. After that, it deposits the payload at a point 277 mm outward and −154 ° shifted from the pickup position.

The obstacle course also contains two obstacles. When not carrying the payload, the hook can swing over the obstacles, but when carrying the payload, the crane has to move around them.

During handling of the crane by various teams of users, the need for recalibration of the sensors may arise, which changes the initial values measured by the crane system with respect to the obstacles. Therefore, for an optimized automated trajectory, it is necessary to set the initial condition by measuring with respect to the environment, independently of the crane's sensor data. Otherwise, as little as one centimeter offset in any direction can lead to hitting the obstacle, which in turn induces oscillation, so that the payload can not be accurately deposited into the goal.

1.2 Modeling of the System

The crane without the payload can be modeled rather accurately as a lightly damped three-dimensional single pendulum and the crane with the payload can be modeled as a lightly damped double pendulum. A nonlinear 4-state dynamic model with states representing radial and tangential deflection angles for the hook and the payload could therefore very accurately describe the system. However, it is very computationally intensive and error-prone to derive such a model. The following simplifications help to obtain a dynamic model that is better to handle:

(1) All angles are assumed to always be small, to obtain linear behavior.
(2) Damping is neglected.
(3) The dynamics in radial and tangential direction are assumed to be decoupled.
(4) Because of symmetry, the oscillation frequencies in radial and tangential direction are identical.

With these assumptions, the system can be simplified to a linear undamped 2-DOF system as depicted in Figure 1. For the single-pendulum case, it is sufficient to set $m_p = 0$. Equations to calculate the period times can be found in [1]. For a cable length of $l_1 = 714\,\text{mm}$ as motivated in Section 2.2 and all other set system parameters, the double pendulum period times evaluate to

$$T_1 = 1.2184\,\text{s} \tag{1}$$
$$T_2 = 2.0993\,\text{s}\ . \tag{2}$$

The single-pendulum period time evaluates to

$$T_s = 1.6942\,\text{s}. \tag{3}$$

2. MANUAL INPUT SHAPER

2.1 Selecting Types of Input Shaper

The model of the system as introduced in Section 1.2 is a double pendulum and a two-mode shaper is suited to minimize the oscillation. In other words, two input shapers are to be convolved together and implemented to successfully reduce the oscillation. Numerous input shaper types can be chosen to minimize the oscillation, e.g. ZV, ZVD, EI. To improve the robustness of the two-mode input shaper, the two shapers to be convolved are initially chosen to be ZVD shapers. However, the time delay of up to 3.3 s introduced by the convolved ZVD shaper proved to be difficult to anticipate by a human operator. In order to make a more easily controllable shaper, the extra robustness is given up for a faster shaping time, thus two ZV shapers are chosen to be convolved instead.

2.2 Selecting Frequency for Input Shaper

To minimize the oscillation, the length of the pendulum should be kept at a fixed number (both the hook to trolley length and the hook to payload length). Keeping the hoist distance constant before picking up the payload and after picking up the payload makes sure the input shaper can remove most of the oscillation. Although the oscillation will be the minimal if the hook is hoisted all the way up, the hoisting speed is so slow that hoisting the hook right above the obstacle instead of all the way up is more optimal. The length from the hook to payload is a set to be 75 cm and the length from the trolley to the hook is determined to be 71.4 cm as shown in Table 1. With the period times of Section 1.2, the input shaper is found to be

$$IS = \frac{1}{4}\delta(t) + \frac{1}{4}\delta(t-0.609) + \frac{1}{4}\delta(t-1.05) + \frac{1}{4}\delta(t-1.66)\ . \tag{4}$$

An overview about impulse times and amplitudes is given in 2.

3. TRAJECTORY GENERATION

3.1 First trajectory: separated movements

To obtain a first working trajectory, a non-smooth trajectory, where hoist and planar movement are never actuated at the same time, is designed. This trajectory will later be improved with respect to time and convolved with an input shaper to obtain better results. With the input shaper and the decoupled model in mind, it is not problematic to perform radial and slew motions at the same time.

Times for crucial movement stages are found by dividing the desired distance by the trolley velocity in that direction. The trolley slew and radial velocities were obtained from [3] and the hoist velocity was measured to be $0.13\,\mathrm{m/s}$. The crucial stages identified to get the payload into the goal are:

(1) Pull up the hook to slew over the obstacles.
(2) Reduce the radius to payload radius.
(3) Slew to payload position.
(4) Lower the hook to pick up the payload.
(5) Wait to make sure the payload magnet is hit by the hook.
(6) Pull up the hook to lift the payload over goal height.
(7) Increase the radius to get around the obstacle.
(8) Slew around the obstacle to goal position.
(9) Reduce radius to goal radius.
(10) Lower hook to put payload in goal.

The times and values of this first trajectory can be found in Table 1. A 3D Picture of this trajectory is shown in Figure 2.

3.2 Second trajectory: joined movements

A two mode ZVD shaper is able two attenuate both modes of the double pendulum when the load is attached and the single pendulum mode without payload. This shaper was chosen due to multiple reasons. First, because the results in [4] show that a ZVD shaper has better oscillation suppression than other simulated and tested shapers therein. Second, for this task the minimization of oscillations was more important than faster operation, as a certain precision is crucial to drop the payload into the target container. Third, there was no human operator who could be deceived by the response delay of the input shaped crane command, compared to the manually shaped attend. Finally, in the case of the automatic execution of the pre-planned trajectory, the additional robustness comes at a low cost of only a few seconds additional time.

The convolution of the parallel motion trajectory with the two mode ZVD shaper not only attenuates vibration, but also results in slightly overlapped moves of the ten stages described in Section 3.1, i. e., the down hoisting in stage (4) started while the slew to payload position in stage (3) was still fading out. This first ZVD shaped trajectory, shown in Figure 3, fulfills the desired task without exhibiting considerable oscillation.

In order to further improve the trajectory, overlap of the different stages was deliberately added. Note that overlap has to be handled carefully during the transition from stage (6) to (7), to avoid dragging the payload from its platform. Another method to further improve the time was to remove the waiting time duration before pickup and dropdown of the payload. The resulting final trajectory can be seen in Figure 4.

4. CONTEST RESULTS

The overall contest results can be found in Table 3. The results of the authoring team were in the center span. The performance problems in manual unshaped operation are due to the fact that the unshaped double pendulum is a chaotic system, so minor deviations in operation yield extremely different oscillation behaviour. This is why success in the manual unshaped category is not predictable.

Due to the fact that a convolved ZV shaper was introduced, the oscillation in our shaped system was noticeably higher than with shapers of other teams. The ability to predict the delay that a ZVD or EI shaper introduces however varies from operator to operator, so this is why the autoring team still feels confident about their choice of shaper.

The calibration effects discussed in Section 1.1, together with imprecise measurement of the initial condition, lead to the fact that the proper starting height had to be guessed in competition without a prior trial run. Therefore, the payload was not picked up in the competition run.

5. CONCLUSION

Manual as well as automated crane operation are not an easy task to fulfill. Although manual crane operation with an input shaper is significantly easier than without one, new challenges with respect to delay in operation arise.

For automated crane operation, the importance of exactly calibrated and measured initial conditions, as well as an exact knowledge of the surrounding is highly important. Since the trajectory is completely known before applying an input shaper, the delay of the input shaper has much less negative effect on a trajectory than on a human operator, which is why more advanced, robust shapers can be used more easily.

REFERENCES

[1] C. J. Adams and K. Sorensen. *Lab 2 – Input Shaping*. Laboratory Handout for Georgia Tech class ME 6404, 2019.

[2] W. Singhose and W. Seering. *Command Generation for Dynamic Systems*. Georgia: Georgia Institute of Technology, 2011.

[3] C. J. Adams and K. Sorensen. *Lab 5 – Trajectory Following*. Laboratory Handout for Georgia Tech class ME 6404, 2019.

[4] D. Blackburn, W. Singhose, J. Kitchen, V. Patrangenaru, J. Lawrence. *Advanced Command Shaping for Nonlinear Tower Crane Dynamics*. The 8th International Conference on Motion and Vibration Control, 2006.

APPENDIX

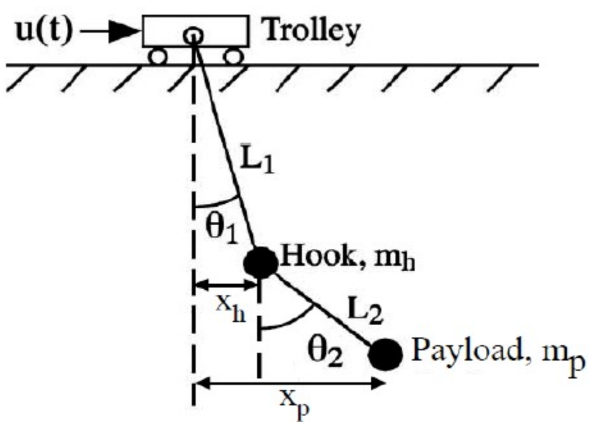

Fig. 1. Model of the simplified system.

Table 1. Movement stages and according time stamps for the initial trajectory.

Stage	Moving part	Start time [s]	End time [s]	Start position	End position
1	Hook	0	6.22	1523 mm	714 mm
2	Radius	6.22	8.08	790 mm	529 mm
3	Angle	6.22	20.08	32 °	310 °
4	Hook	20.08	25.96	714 mm	1478 mm
5	None	25.96	27.96	–	–
6	Hook	27.96	33.83	1478 mm	714 mm
7	Radius	33.83	36.70	529 mm	930 mm
8	Angle	33.83	41.46	310 °	157 °
9	Radius	40.07	41.46	930 mm	736 mm
10	Hook	41.46	43.12	714 mm	930 mm

Table 2. ZV shaper for manual operation.

Time	Time [s]	Amplitude
0	0	0.25
$\frac{T_1}{2}$	0.6092	0.25
$\frac{T_2}{2}$	1.0497	0.25
$\frac{T_2}{2} + \frac{T_2}{2}$	1.6589	0.25

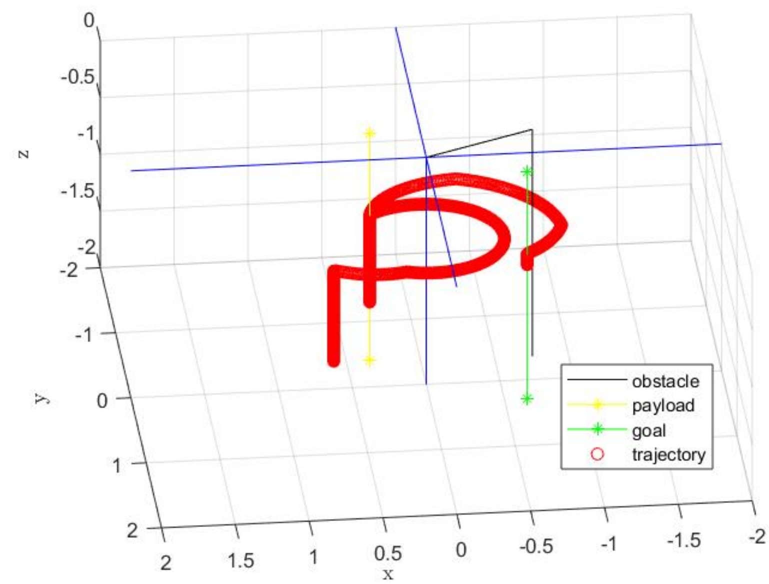

Fig. 2. Initial trajectory.

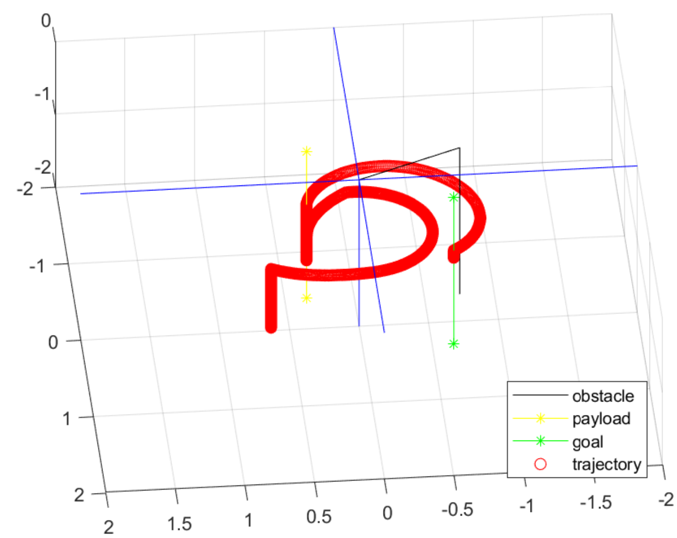

Fig. 3. ZVD shaped trajectory with unintentional overlap through time delay.

Table 3. Contest Results.
Successful: (S), Unsuccessful: (US).
Winning team shown in red, author team shown in bold.

Teams	Manual Unshaped	Manual Shaped	Planned Trajectory
1	92s (S)	60s (S)	37s (US)
2	105s (US)	64s (S)	40s (S)
3	68s (S)	76s (S)	39s (US)
4	51s (S)	76s (S)	57s (US)
5	**94s** (S)	**71s (S)**	**38s (US)**
6	121s (S)	65s (S)	60s (S)

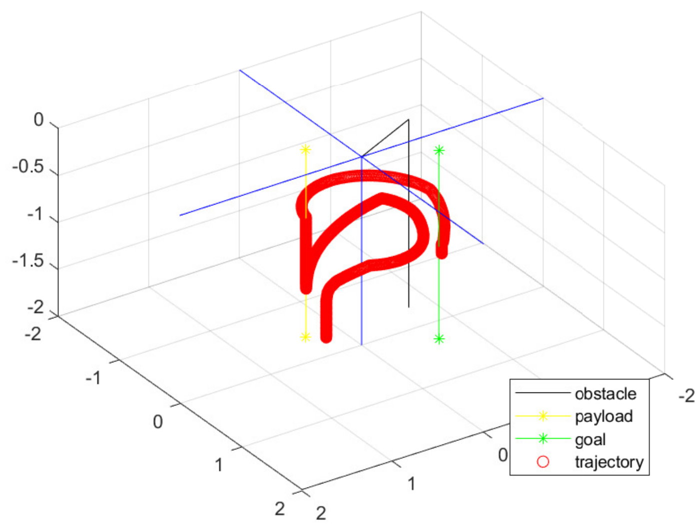

Fig. 4. ZVD shaped trajectory with additional intended overlapping for time optimization.