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# Part A

## Introduction problems

Firstly, we analyse and define the control problem to be solved. The task is to implement an MP controller for a gantry crane, capable of tracking a given square in XY (horizontal) plane. The square is to be tracked by the mass suspended from the crane and not necessarily the crane itself.

This problem can be deconstructed into 4 separate problems of moving the mass from a given point A to a given point B. The four movements are then executed in sequence, such that the mass tracks the required square in the end. This definition of the problem allows for the use of controller implemented for previous assignments with only minor changes.

A choice was made to use controller with only hard constraints instead of controller with soft constraints implemented. The controller with soft constraints takes significantly longer to compute, since the slack variables increase the size of the system to be optimised [1]. In testing, the controller did not compute the solution in time (solutions took more than 1 second with sampling time of 1/30 seconds). Moreover, the settling times of controlled variables of hard constrained controller were shorter.

## Algorithm

The first step is to define the square to be tracked. Since the problem is posed as moving the crane from a given point A to a given point B, the square is defined by 4 points in its corners. These points should be far apart, to avoid problems connected with the stickiness of the crane (larger force required to begin moving it). If the controller exerts large force to overcome the stickiness, it would risk overshooting the corner of a small square. The square is oriented so that its sides are parallel with the X and Y axes. This simplifies the definition of the constraints (as explained later). Moreover, this way the movement along each side is controlled by one actuator only any oscillations are controlled more easily.

In the laboratory sessions, it was also noted that the crane experiences larger stickiness in the X-axis than in the Y-axis. This is because in the X-axis larger mass (crane car and rail it moves on) has to be moved than in the Y-axis (crane car only). To ensure a square is tracked instead or a rectangle, a stickiness correction constant is introduced to the code. This constant is added to the higher X coordinate of the corners and subtracted from the lower X coordinate. By doing this, the controller is set to track a rectangle, but due to stickiness it will track a square. Value of this constant is best set experimentally in real hardware. In the simulations, the increased stickiness is not well modelled, and hence the value of the constant is set to zero.

After the target states (i.e. the corners of the square) are defined, the constraints are defined too. The constraints are imposed on the same states as in the previous assignments – on X and Y position and on X and Y angle. The constraints set on angle are constant. The position constraints are different for the four different target states. For each state, the position constraint is a thin rectangle with shorter sides lying on the previous and current target state and longer sides parallel to the side of the square. The constraint is defined by variable *margin*, which is the distance of the longer side from side of the square.

Using the notation from lectures and previous assignments, the only matrices that are affected by the existence of 4 different constraints are the *b* constraint matrices. Therefore, there must be 4 sets of calculations performed in the initialisation stage of the program. The constraint matrices *bb* and target states are then cycled through based on the time of simulation/run of the hardware. Time of the simulation is divided by distance between two adjacent states (i.e. length of the side of the square) to ensure longer time is allowed for larger squares tracked. This result is then multiplied by a constant *warp*, by which the action of the controller can be sped up or slowed down. Remainder after division by 4 is then calculated from this time control signal to pick the appropriate state and constraint matrix from the set of 4.

## Results and discussion

To evaluate the controller, a metric of “squarness” was developed. The trace of the pendulum was estimated from the simulation data (position and angle) by assuming length of the string. Even though this is not accurate calculation, it is still informative, as it involves the angular deviation of the string (i.e. oscillations). Smallest possible rectangle is then circumscribed and largest possible rectangle inscribed to the trace. The difference in the areas of these two rectangles gives then the rectangular area the pendulum sweeps. The smaller this area, the less oscillation the pendulum experiences and the more perfect is the square tracked. Note that rectangles were used in this method, since any deviation from perfect square shape can be readily solved by adjusting the stickiness correction variable.

Using this metric, the parameters of the controller were tuned using trial and error. The final set of the parameters is given in Table I below.

1. parameters of the best controller

|  |  |  |  |
| --- | --- | --- | --- |
| **Q(1,1), Q(3,3)** | 10 | **TS** | 1/30 |
| **Q(2,2), Q(4,4)** | 1 | **Angle constraint** | 5 deg. |
| **Q(5,5), Q(7,7)** | 50 | **N** | 20 |
| **Q(6,6), Q(8,8)** | 2 | **Margin** | 0.001 |
| **R(1,1), R(2,2)** | 0.01 | **Warp** | 0.1 |
| **P(1,1), P(3,3)** | 5 |  |  |
| **P(5,5), P(7,7)** | 30 |  |  |

The trace of the best controller (i.e. the one with smallest area traced) is shown in Fig. 1 below. A case can be made for the controller which trace is shown in Fig. 2, since its trace is smoother (without oscillation in the corners) and may be more appealing to a human observer. This controller has the same parametrisation as the best one, apart from warp = 0.18. The solutions of both controllers calculated in time (i.e. quicker than the sampling time) and performed better than the non-constrained controller, which suffered significant oscillations in the corners.

There are few points to be noted. First, by optimising the parameters for non-linear simulation, the performance of the linear simulation suffered. This can be attributed to the mismatch between the two models. Linear simulation was also more sensitive to tight constraints margin, and could only run with margin = 0.03. Lower margin, however, improved the performance of the non-linear simulation. In the best simulation, the crane is doing small stabilising movements around the corners to minimise the oscillations. This, however, might not be possible in reality due to the stickiness of the crane.

# Part B

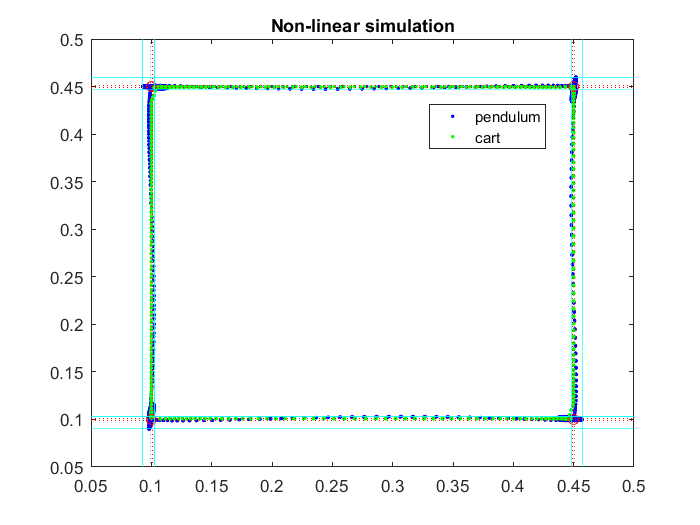


Figure 1: trace of the best controller, red dashed lines are constraints, cyan lines are inscribed and circumscribed rectangles

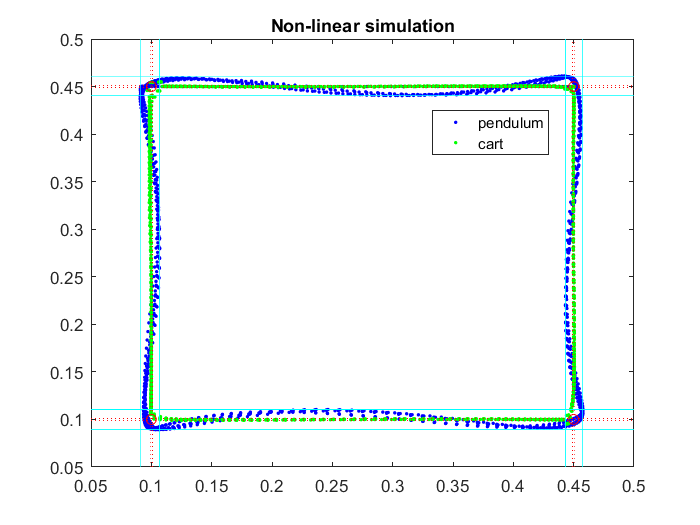


Figure 2: trace of the smoother controller, constraints in red dashed lines, inscribed and circumscribed rectangles in cyan

This problem can be deconstructed into 4 separate problems of moving the mass from a given point A to a given point B. The four movements are then executed in sequence, such that the mass tracks the required square in the end. This definition of the problem allows for the use of controller implemented for previous assignments with only minor changes.

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1. Table Type Styles

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| Table column subhead | Subhead | Subhead |
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a. Sample of a Table footnote. (Table footnote)

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# Conclusion

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Appendix

Appendixes should appear before the acknowledgment.

Acknowledgment

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