ORC Assignment 1

Saviane Arianna mat. 240602

Titton Giulia mat. 240311

October 2023

Contents

1 Question 1

1.1 IC versions comparison

The first request is aimed at stabilizing a desired position of the end effector starting from an initial configuration using different versions of IC controllers.

Impedance control requires to tune the desired dynamics matrices K (stiffness matrix) and B (damping matrix). In this case of study, these matrices have been generated after some trials imposing the following values:

$$K = \begin{bmatrix} 10000 & 5000 & 5000 \\ 5000 & 10000 & 5000 \\ 5000 & 5000 & 10000 \end{bmatrix} \quad B = \begin{bmatrix} 300 & 200 & 200 \\ 200 & 300 & 200 \\ 200 & 200 & 300 \end{bmatrix}$$

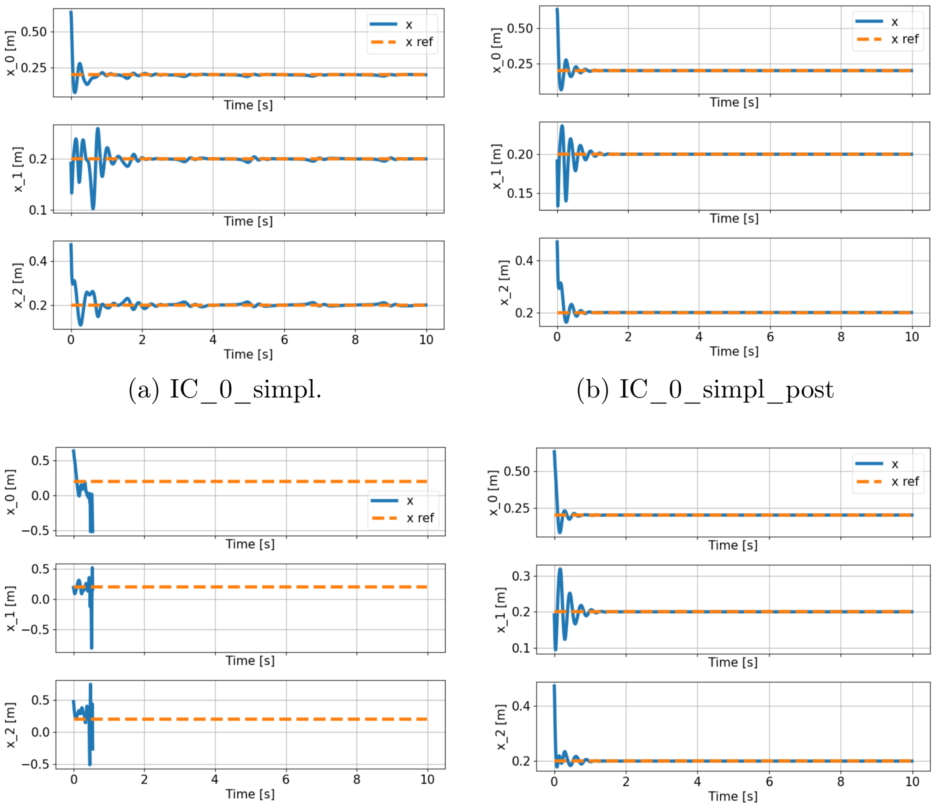
Notice that K and B are 3x3 matrices (as the inertia matrix Λ) according to the dimensions of the operational space of the end effector.

The first test, simulating a Coulomb friction value equal to 0, shows the values reported in Table 1 regarding the average tracking error of the different versions of IC controllers.

Average tracking error	
Controller	Error
IC_0_simpl	13 mm
IC_0_simpl_post	6 mm
IC_0	nan
IC_0_post	6 mm

Table 1: Average tracking error without friction

According to the above-mentioned results and to the position, velocity, acceleration and torques plots, the best controller is the last one, implementing the exact version of IC together with the postural task. This controller has the capability to converge to the desired position in a smaller time period while maintaining position, velocity and acceleration values stable after the transient. The worst controller is the third one (IC exact version), which is not able to converge to the desired position. The first controller manages to accomplish the task with some oscillations especially in the second and third end effector coordinate (and in joint torques accordingly), taking a slower time to converge with respect to "IC_0_post". The controller "IC_0_simpl_post" performs better than the simplified IC version without postural task and the results are similar to the ones of "IC_0_post", with slightly larger converging time. The results of the first test are shown in Figure 1.



(a) IC_0_simpl. (b) IC_0_simpl_post

(c) IC_0 (d) IC_0_post

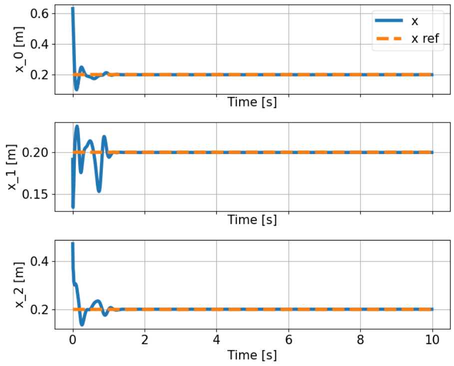
Figure 1: First test position plots.

The second test, which considers a Coulomb friction coefficient equal to 2% of the maximum torque at each joint, provides the results shown in Table 2.

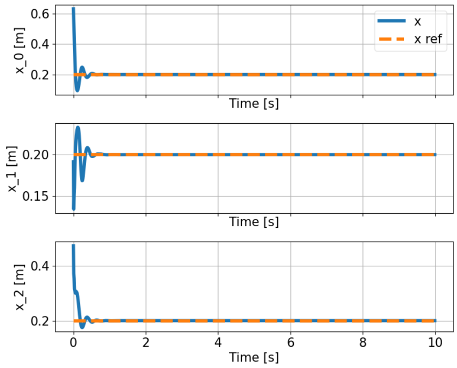
Average tracking error	
Controller	Error
IC_0_simpl	7 mm
IC_0_simpl post	4 mm
IC_0_	14 mm
IC_0_post	6 mm

Table 2: Average tracking error with friction

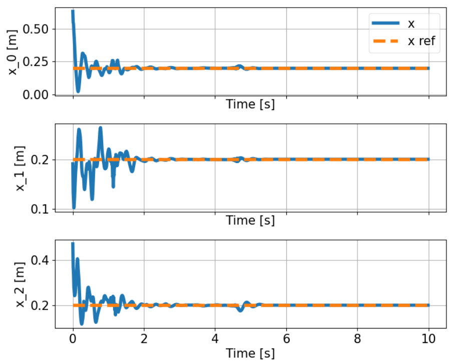
Comparing the results with the ones obtained in the first test, there is a considerable improvement in the "IC_0_simple" controller which converges to the desired position without oscillations; controller 2 and 4 slightly improve their performance but do not seem to be affected by friction as much as the first one. Controller 3 manages to converge despite showing relatively large oscillations in the first time instants and some smaller deviations from the desired position after a while regarding all the three coordinates. The convergence time is much higher in comparison with the other controllers, particularly with respect to the ones which implement the postural task. Figure 2 shows the results of the second test.



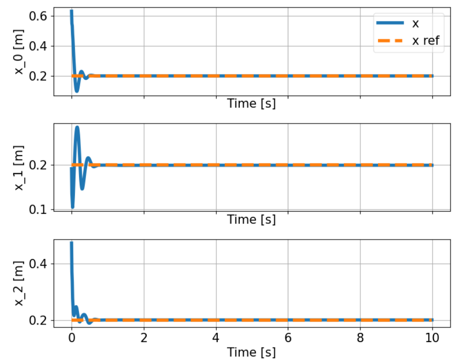
(a) IC_0_simpl.



(b) IC_0_simpl_post



(c) IC_0



(d) IC_0_post

Figure 2: Second test position plots.

Figure 3 compares the average tracking error of the controllers in both tests.

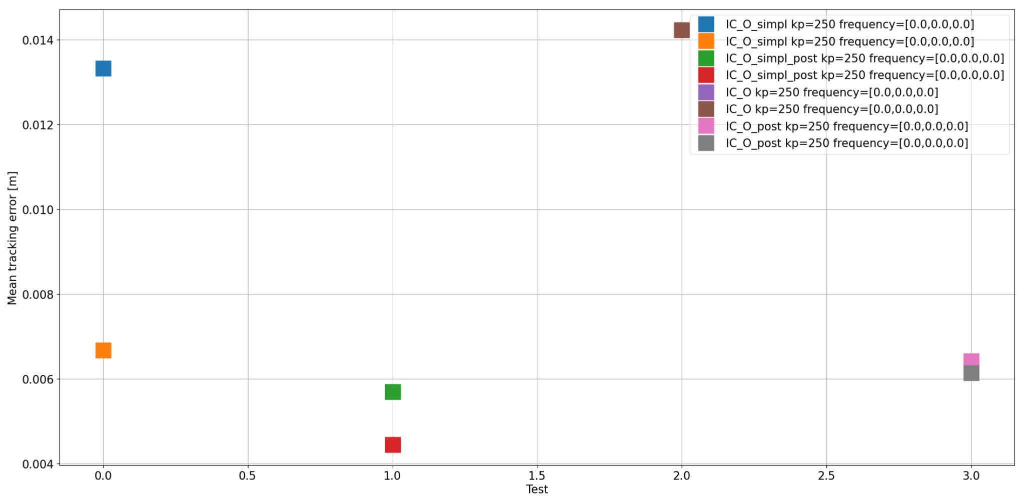


Figure 3: Comparison between average tracking errors.

1.2 Exact IC divergence

The controller “IC_0” fails to stabilize the end effector position. This may be caused by redundancy, in fact joint space is 6-dimensional while end effector space has 3 dimensions. The additional degrees of freedom in the joint space are not forced to follow a specific path and they can move freely; consequently, no constraints are imposed in the free degrees of freedom and this may lead to divergence. Controller “IC_0_post” prevents this problem trying to stabilize the joint configuration around a specific trajectory and is able to successfully accomplish the task indeed. The same happens for the second controller (“IC_0_simpl_post”), which implements the postural task too. The first controller seems to converge despite not considering the postural task; in this case, bias forces are provided directly in the joint space in an approximated way (h) that is accurate only if joint velocities have low values. Having redundancy, joints can freely assume high velocities and the approximation given by the simplified version of the IC controller cannot hold. As a consequence, simulation shows convergent results because of the approximation of bias forces but they may be inconsistent.

2 Question 2

2.1 OSC and IC comparison

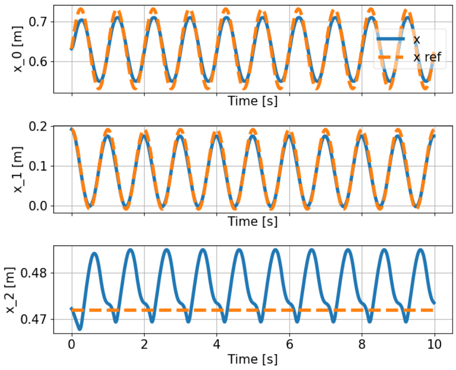
The second task is to stabilize a reference trajectory oscillating at different frequencies comparing OSC and IC performances (both implementing the postural task).

In general, the best controller is the IC one. Both of them do not follow the trajectory in a desirable way mainly in the third end effector coordinate. In OSC case, the average tracking error is higher than IC one and at high frequency the actual position oscillates around a value which is different from the desired one, causing an offset in the position on that coordinate. IC shows higher oscillations at high frequency, but with a smaller drift (oscillations are around the correct values). IC performance are much better at low frequencies. The average tracking errors in the different cases are reported in Table 3.

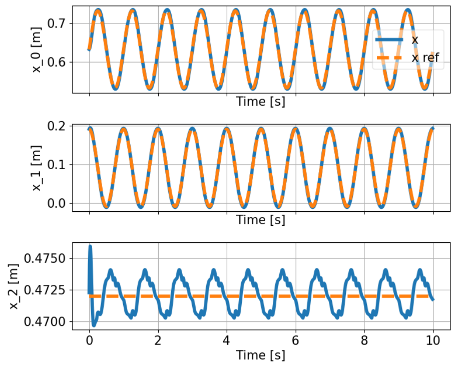
Average tracking error	
Controller	Error
OSC low frequency	18 mm
IC low frequency	5 mm
OSC high frequency	77 mm
IC high frequency	53 mm

Table 3: Average tracking error of OSC and IC

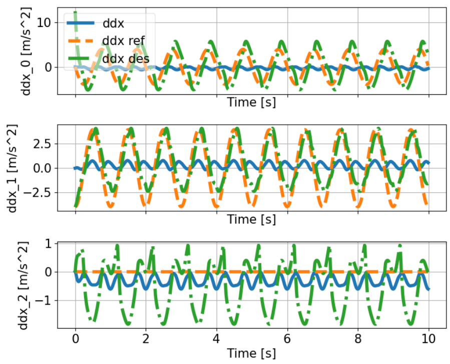
Figure 4 compares the performance of OSC and IC controllers at low frequency.



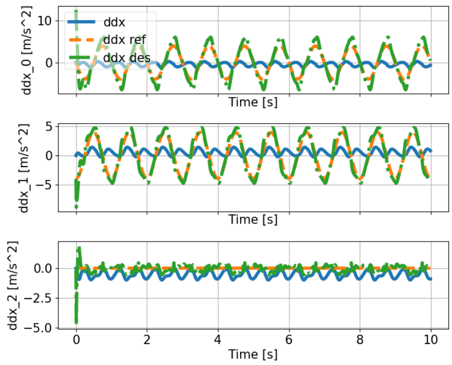
(a) OSC position



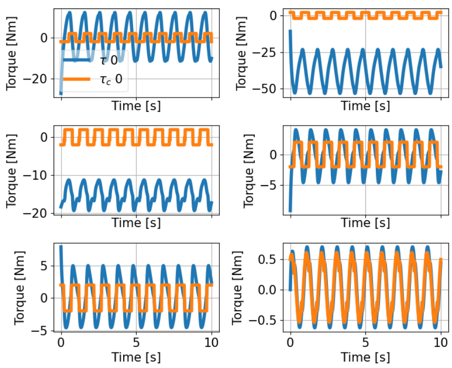
(b) IC position



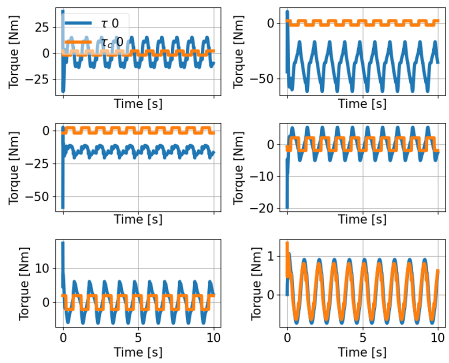
(c) OSC acceleration



(d) IC acceleration



(e) OSC torque

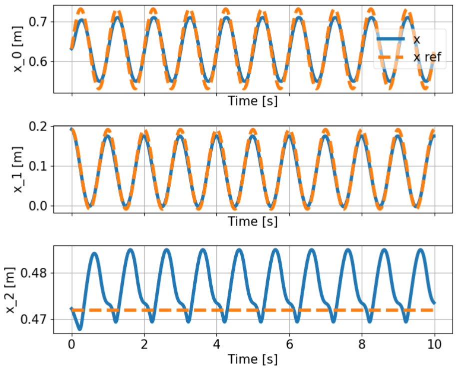


(f) IC torque

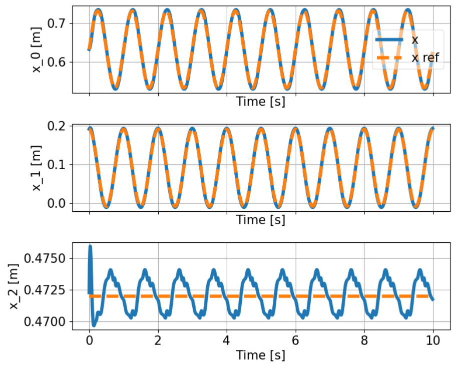
Figure 4: Comparison between OSC and IC at low frequency.

OSC larger errors in tracking position are mainly given by the fact that the difference between desired and actual accelerations are high. In general, actual accelerations are much lower than desired ones while joint torques are higher than the reference ones. The same happens also in the IC case, but with smaller errors mainly at low frequencies. Moreover, torques and accelerations for the IC controller are higher than OSC case, especially regarding the first time instants at low frequency; at high frequency, instead, the requested values are larger not only in the first time interval but during the whole simulation time.

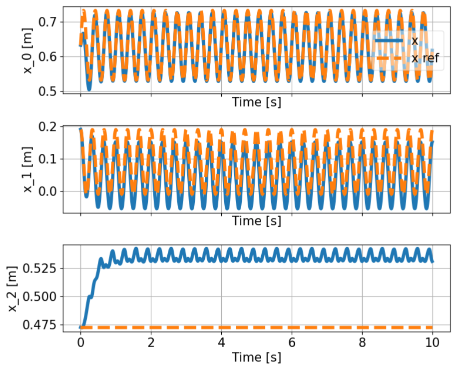
Figure 5 compares the tracking error of OSC and IC both at low and high frequency.



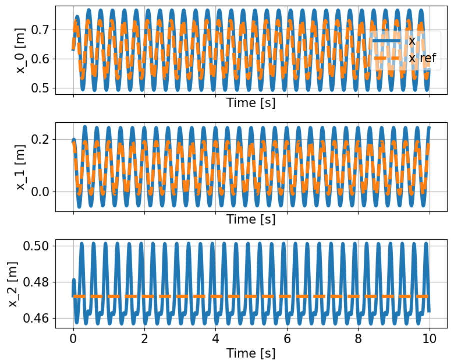
(a) OSC position at low frequency.



(b) IC position at low frequency.



(c) OSC position at high frequency.



(d) IC position at high frequency.

Figure 5: Comparison between OSC and IC at low and high frequency.

Generally speaking, performances decrease for both controllers at higher frequency and the error grows more in the IC case, that still remains the best choice despite a relative error growth which is more than twice as much as the one of OSC (IC error increases from 5 mm to 53 mm while OSC goes from 18 mm to 77 mm).

2.2 Parameters tuning

The aim is to tune the parameters of the control laws in order to obtain better performances of the OSC and IC controllers. The only parameter to change is the proportional gain "kp". Consequently also the derivative gain "kd" is re-tuned as $2 * \sqrt{kp}$.

The approach used consists in rewriting the code in order to loop until a given condition is satisfied, keeping the stiffness and damping matrices unchanged with respect to the initial guess. In the low frequency case, the conditions are the following:

- OSC controller is set to reach an average tracking error of 1,4 mm
- IC controller is set to reach an average tracking error of 5,1 mm

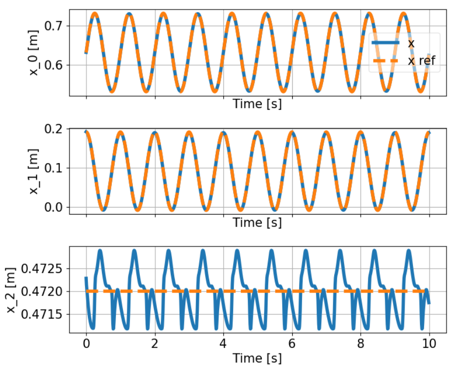
The results of the intermediate iterations are shown in Table 4 and Table 5, while the plots are displayed in Figure 6. The OSC controller doubles the value of kp while the error is halved. The IC controller, instead, does not show a wide range of possible kp values.

Average tracking error and Kp of OSC	
Error	Kp
4,7 mm	700
2,3 mm	1500
1,6 mm	2100
1,4 mm	2400

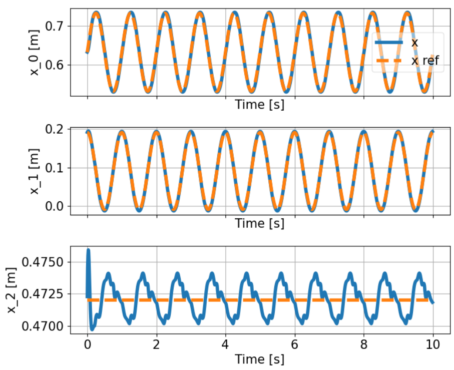
Table 4: Average tracking error and Kp of the controller OSC at low frequency

Average tracking error and Kp of IC	
Error	Kp
5,1 mm	650
5,07 mm	700

Table 5: Average tracking error and Kp of the controller IC at low frequency



(a) OSC low freq.



(b) IC low freq

Figure 6: Plots of OSC and IC controllers at low frequency

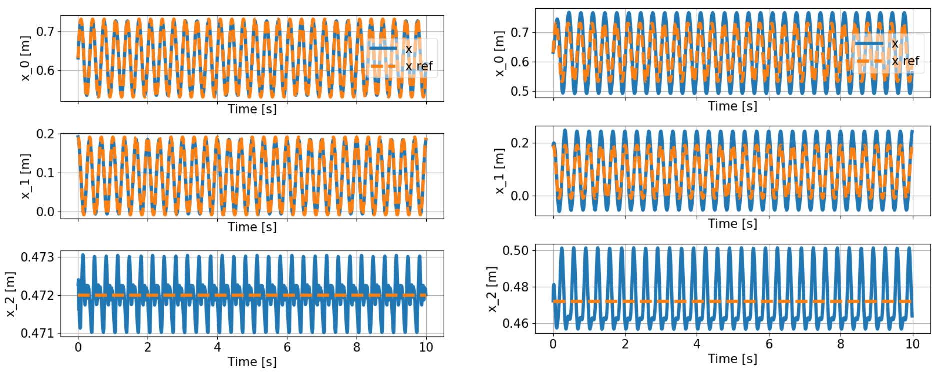
In the high frequency case, instead, the values of Kp are reported to be higher in the case of OSC controller, more or less twice the OSC controller at low frequency, and lower in the case of IC controller. In this last scenario, kp is 7 times smaller than the IC at low frequency, with an average tracking error 10 times larger. The results of the intermediate steps are reported in Table 6 and in Table 7 and the plots are displayed in Figure 7.

Average tracking error and Kp of OSC	
Error	Kp
12 mm	700
5,6 mm	2000
3,8 mm	3200
3 mm	4200

Table 6: Average tracking error and Kp of the controller OSC at high frequency

Average tracking error and Kp of IC	
Error	Kp
56 mm	60
52,2 mm	80
51,2 mm	100

Table 7: Average tracking error and Kp of the controller IC at high frequency



(a) OSC high freq.

(b) IC high freq

Figure 7: Plots of OSC and IC controllers at high frequency

In conclusion, after the convergence to a result of the code, the final average tracking errors are 1,4 mm for the OSC and 5,07 mm for the IC at low frequency, while the final average tracking errors are 3 mm for the OSC and 51 mm for the IC at high frequency.

2.3 Robustness test

According to the instructions, the flag of "randomize_robot_model" has been set to 1 in the configuration file, in order to test the robustness of the controllers to modelling errors, keeping the values of kp found in the previous section.

Running each test, we report the results of each controller both in the low frequency setting and in the high frequency setting.

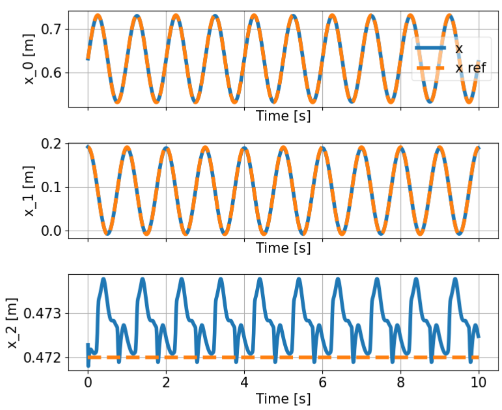
The OSC controller at low frequency with a random model always presents an average tracking error of 2 mm, the same as the OSC controller in the previous configuration. The only difference lies in the position of the third end-effector coordinate, which has an offset with respect to the reference value.

The IC controller at low frequency shows a range of average tracking errors of 1 mm with respect to the tracking errors computed in the previous section (2.1). Running the code multiple times, the plots show no difference with the previous section. Fig. 8 shows these first 2 configurations.

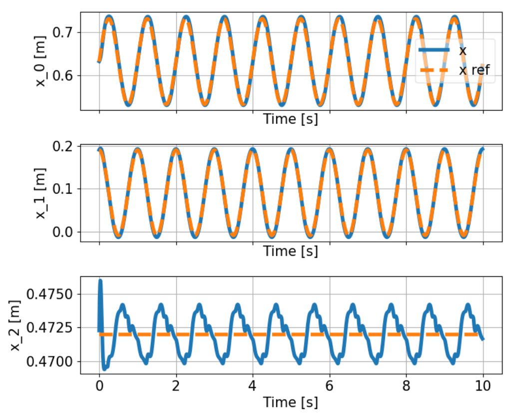
The OSC controller at high frequency presents a particular behaviour. It does not always converge to a solution, so it results particularly unpredictable. When a solution is reached, the average tracking error differs from the one computed in the previous section of 1 mm. In the best random configuration it reaches an average tracking error of 4 mm. The plots show a behaviour similar to the OSC at low frequency: an offset is present with respect to the reference value.

Lastly, the IC controller at high frequency provides a range of average tracking error quite large. The minimum error that the configuration reaches is 49 mm, and the maximum one is 89 mm. The plots display a lot of oscillations in the behaviour of the controller and a large offset with respect to the reference value. Fig. 9 shows the last 2 configurations.

In conclusion, the results computed and the plots demonstrate that the most robust controller to the modelling errors is the OSC at low frequency, which has always the same average tracking error, while the least robust controller is the IC at high frequency, because of its wide range of possible errors.

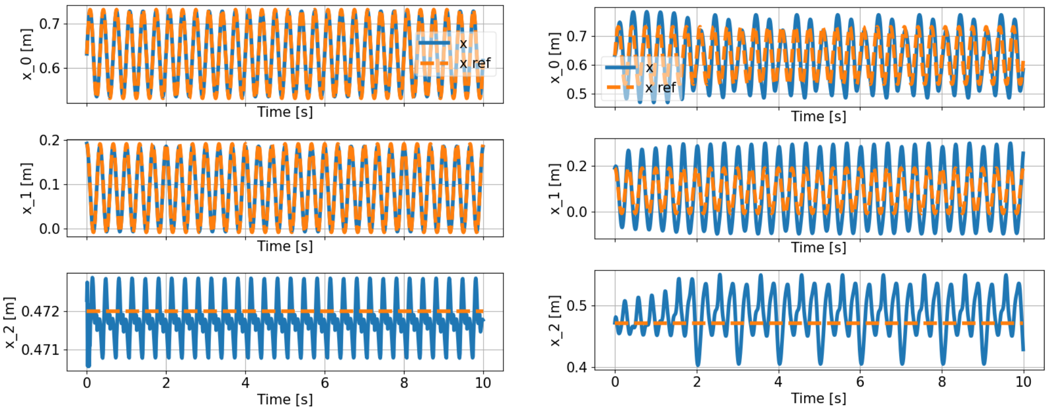


(a) OSC random model



(b) IC random model

Figure 8: Plots of OSC and IC random models at low frequency



(a) OSC random model (b) IC random model

Figure 9: Plots of OSC and IC random models at high frequency