RoVi1

Final Project

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Project Description

1 Tracking points using image Jacobian

We have implemented algorithm for visual servoing in this part. For this part we selected specific marker points as described in problem statement and use mathematical camera model to get image pixel coordinates of the points. Image recognition thus wasn't used in this part.

To compute joint updates it was first needed to compose matrix $\boldsymbol{Z}_{image}$ as described in Robotics Notes:

$$\boldsymbol{Z}_{image}(\boldsymbol{q}) = \boldsymbol{J}_{image}\boldsymbol{S}(\boldsymbol{q})\boldsymbol{J}(\boldsymbol{q}) \tag{1}$$

where $\boldsymbol{J}(\boldsymbol{q})$ is manipulator Jacobian. For its computation we used function from RobWork library. $\boldsymbol{J}_{image}$ is image Jacobian matrix. We implemented function for its computation called `calculateImageJ` which can be found in the file `inverseKinematics.cpp`. We used fixed value for z coordinate. Since we used frame `cameraSim` to model the camera we set $z = -0.5$ for every function call. Finally matrix $\boldsymbol{S}(\boldsymbol{q})$ was composed by inserting transpose of the rotational matrix $\boldsymbol{R}_{base}^{tool}$ twice to its diagonal.

The next information necessary to compute joints updates is difference or move of target points $\overrightarrow{\boldsymbol{dU}}_{image}$. We have programmed function `calculate_dUImage` to solve for $\overrightarrow{\boldsymbol{dU}}_{image}$.

Having matrix $\boldsymbol{Z}_{image}$ and $\overrightarrow{\boldsymbol{dU}}_{image}$ it was possible to solve for joint positional update $\boldsymbol{dq}$ using method of Linear Least Squares.

We adapted two equations from robotics notes into single expression for $\boldsymbol{dq}$ computation:

$$\boldsymbol{dq} = \boldsymbol{Z}^T \left(\boldsymbol{Z}\boldsymbol{Z}^T\right)^{-1} \overrightarrow{\boldsymbol{dU}}_{image} \tag{2}$$

In this equation we used $\boldsymbol{Z}$ to denote $\boldsymbol{Z}_{image}$. For this solving of this LSM problem we have implemented function `compute_dQ_LSM` which can be found in `inverseKinematics.cpp`.

`algorithm2` is the function, where are all of described functions organized together to compute joint updates $\boldsymbol{dq}$ base on the manipulator state and the error in image coordinates $\overrightarrow{\boldsymbol{dU}}_{image}$.

We have implemented J_{image} and $\overrightarrow{\boldsymbol{dU}}_{image}$ composition in a scalable way, so the same functions can be used to track one or multiple target points.

Model of the robot manipulator has velocity limits on joint movements, so it was necessary to check if the limits were satisfied before joint updates. We did so by measuring time for inverse kinematics computations τ_1, subtracting this time from workcell update period specified by $\Delta T \longleftrightarrow$ `deltaT` and finally we divided update $\boldsymbol{dq}$ by the result of subtraction. Velocity of joint movement is the result of the operation:

$$\dot{\boldsymbol{q}} = \frac{\boldsymbol{dq}}{dt} = \frac{\boldsymbol{dq}}{\Delta T - \tau_1} \tag{3}$$

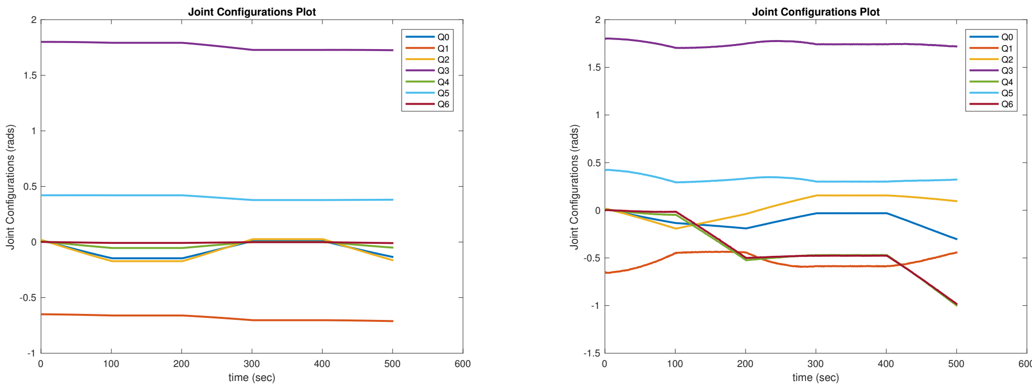
By comparing the actual velocity with manipulator limits it was possible to find out if the limits are satisfied. If they aren't algorithm simply saturate joint movement in order to hold all conditions. For comparison and saturation, function `saturateDQ` was implemented.

In the following section we provide simulation results from tests of inverse kinematics.

1.1 Simulation Tests

During simulations, we recorded joint configurations, tool/camera frame position and orientation for `deltaT` $= 1000ms$ and finally we performed tests for different values for `deltaT` in the range $50\,ms <$ `deltaT` $< 1000\,ms$ and plotted maximum errors of $\overrightarrow{\boldsymbol{dU}}_{image}$

Slow Marker Sequence



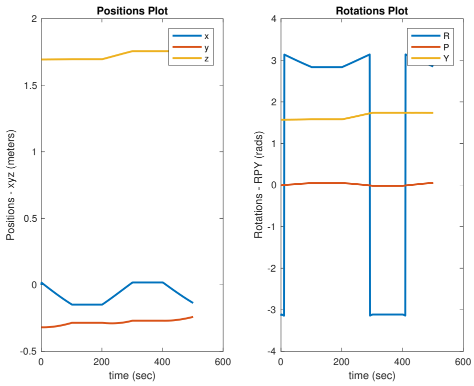
(a) Tracking Single Point (b) Tracking 3 Points

Figure 1: Joint configurations

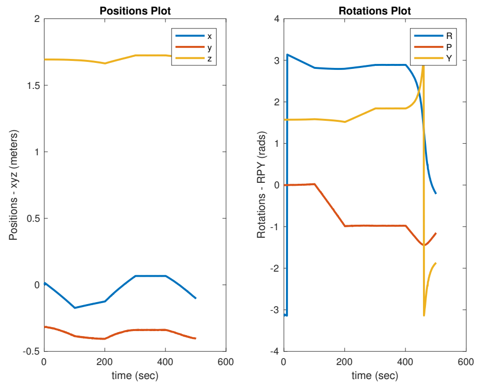
There are differences between joint coordinates for tracking single and 3 target points in the graphs 1a and 1b. The reason behind this is following. When the manipulator is tracking single point, it just follow its position. There is no orientation information about the marker when using single tracking point. Whereas during following of 3 target points, orientation of the marker gains important role, as the manipulator is trying to rotate its tool/camera frame to align its position and orientation with the marker.

In figure 2a and 2b are apparent jumps in roll angle around z axis. This however doesn't imply jumps in tool orientation. Abrupt jumps in the graphs were caused because of switching between $-\pi$ and π rad angle. In the real world, change in orientation is small. Implementation of Robwork transformations probably keeps all orientation angles in the interval $\langle -\pi,\ \pi \rangle$.

Simulation for different ΔTs



(a) Tracking Single Point



(b) Tracking 3 Points

Figure 2: Tool pose transformations

Simulation for different ΔTs

There are plotted maximum pixel errors on the figure 3.

For timing purposes we used C++ Chrono library, for taking time instant of start of the computation of updates and the end instant. For differentiation of joint updates and subsequently getting of velocity, we used difference of these two time stamps divided time which left for joints update.

As you can see on the figure 3 we didn't reach manipulator velocity limits in the interval $\Delta T \in \langle 0.05, 1\rangle\,[s]$ as was described in the problem statement.

For this reason we lowered the interval to the $\Delta T \in \langle 0.005, 0.02\rangle\,[s]$. And in this case, there is apparent increase in the maximum errors for low ΔT. Results are plotted in the figure 4.

Due to non-real time OS, results might be different for each simulation and doesn't offer precise information. However for the purpose of the school exercise, we were able to limit joints speed velocities according to problem statement.

Medium Marker Sequence

The same problems and explanation apply for the Medium marker sequence. Joint coordinates and tool positions are plotted on the graphs 5 and 6. Only difference from Slow sequence is in the time axis. Due to faster and larger movements time span is shorter.

Simulation for different ΔTs

There are plotted maximum pixel errors on the figure 7. Again, we didn't reach manipulator velocity limits in the original interval. Results after lowering the interval of ΔT are plotted in the figure 8.

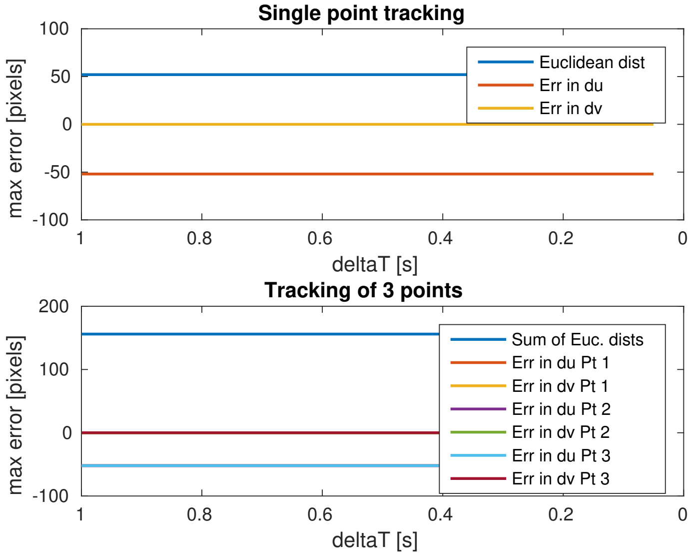


Figure 3: Maximum errors during Slow Sequence Marker following

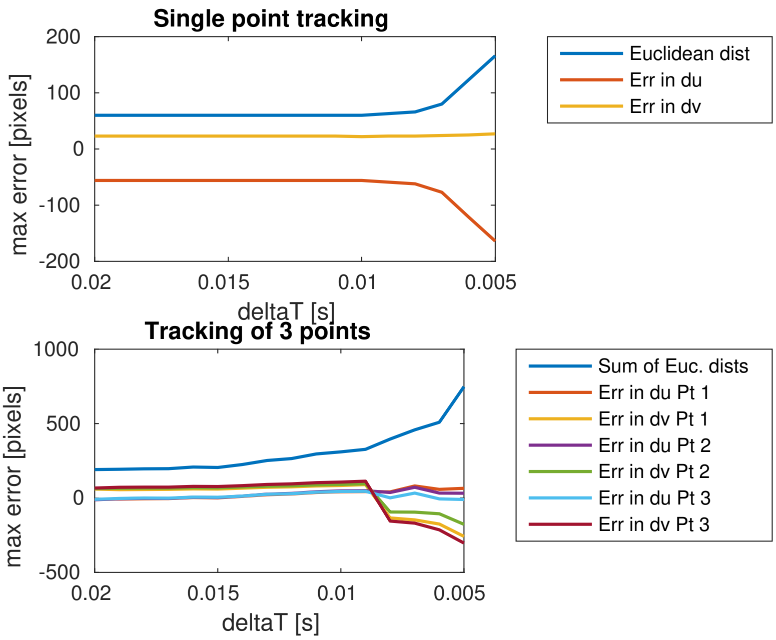
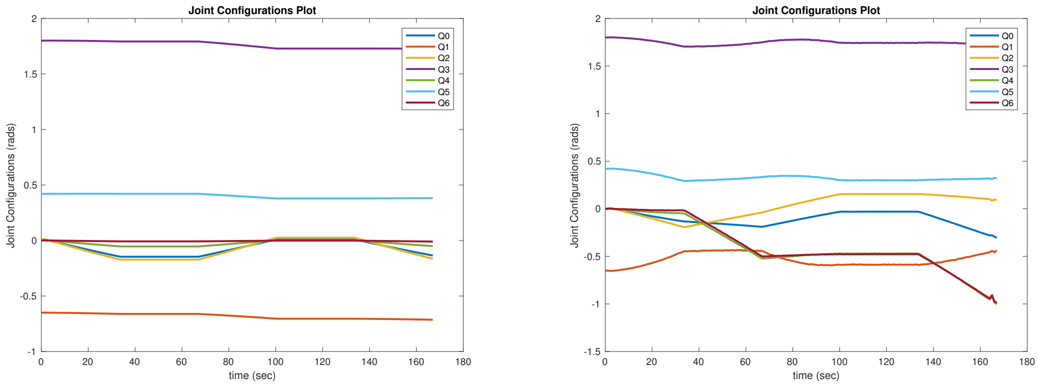
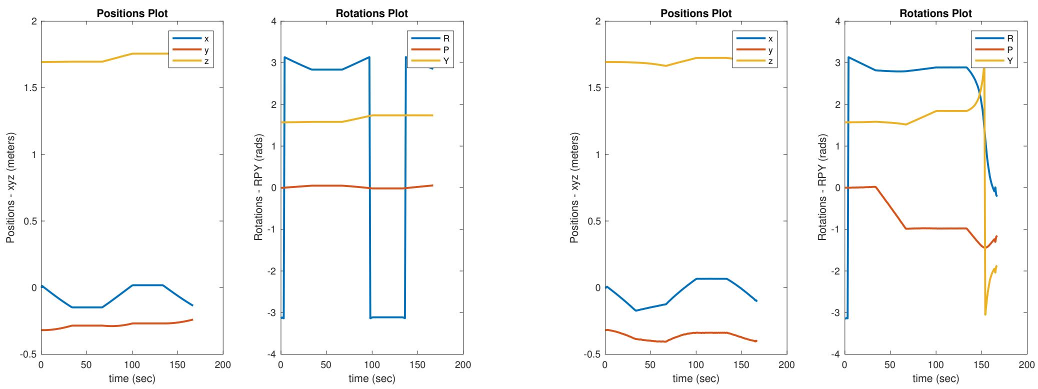


Figure 4: Maximum errors during Slow Sequence Marker following



(a) Tracking Single Point (b) Tracking 3 Points

Figure 5: Joint configurations



(a) Tracking Single Point (b) Tracking 3 Points

Figure 6: Tool pose transformations

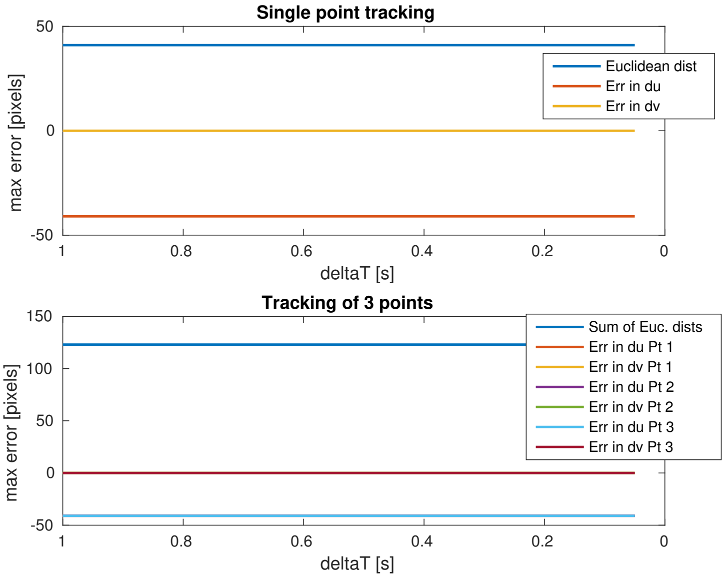


Figure 7: Maximum errors during Medium Sequence Marker following

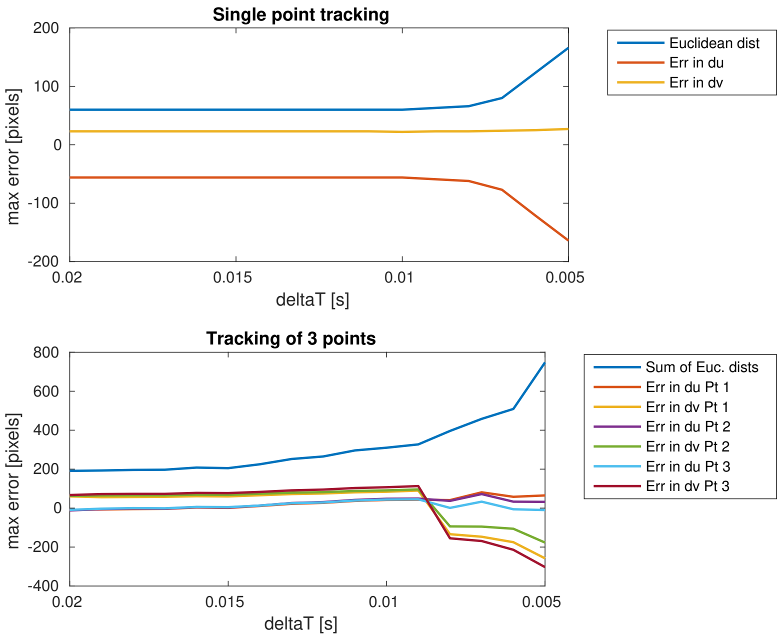
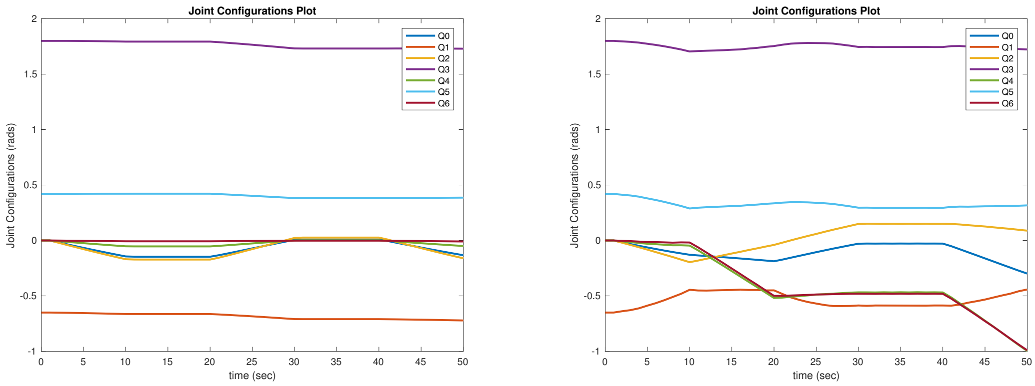


Figure 8: Maximum errors during Medium Sequence Marker following

We have to state the same as for the preceding test. All timing tests were performed on the regular laptop PC, running non-real time operating system. So results from another tests can differ.

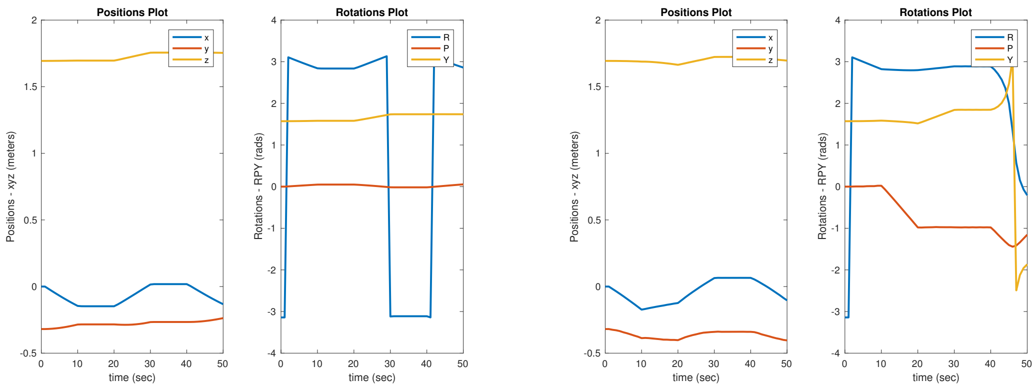
Fast Marker Sequence

Joint coordinates and tool positions are plotted on the graphs 9 and 10. Span of time axis is again shorter.



(a) Tracking Single Point (b) Tracking 3 Points

Figure 9: Joint configurations



(a) Tracking Single Point (b) Tracking 3 Points

Figure 10: Tool pose transformations

Simulation for different ΔTs

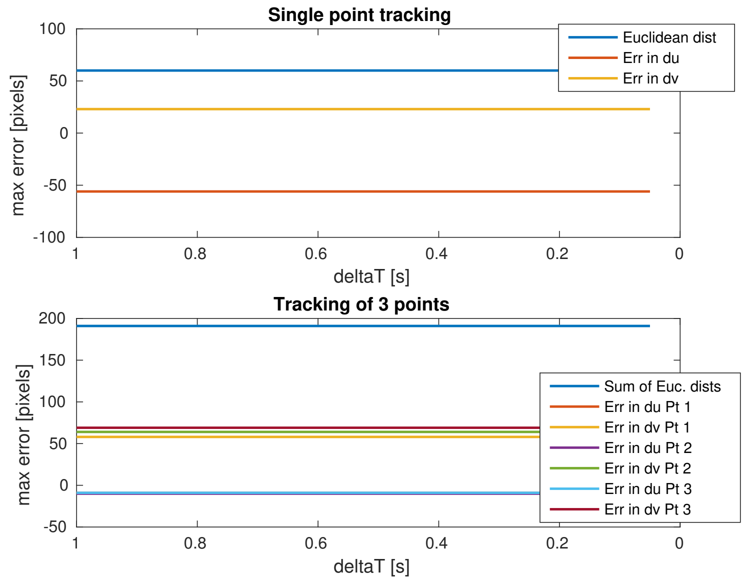


Figure 11: Maximum errors during Fast Sequence Marker following

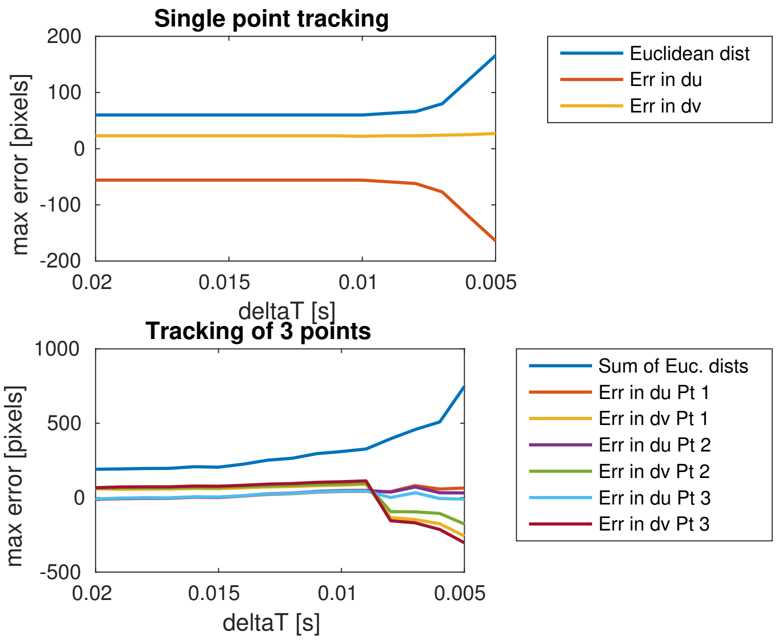


Figure 12: Maximum errors during Fast Sequence Marker following

There are plotted maximum pixel errors on the figure 11 for original interval. Results from simulations for lower interval are plotted on the figure 12.

Conclusion for different speed sequences

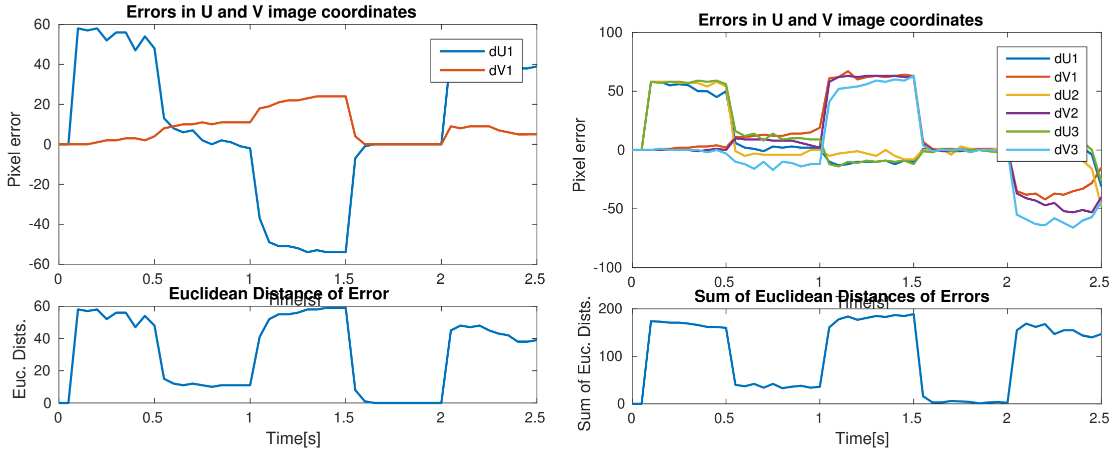
Even though timing and velocity computation during test simulations wasn't precise due to non-realtime of the OS, we can conclude some final facts. Manipulator was able to follow the marker for each sequence with `deltaT` $> 0.01s$. The reason behind these results is probably very short time needed for inverse kinematics computations. We found out is in the order of microseconds, whereas simulation were performed for ΔTs which were one order in magnitude larger (miliseconds). These results will be also different when simulated on different computer.

2 Combining feature extraction and tracking

For the last part of the project we have chosen the Marker 1 for image recognition. Image recognition was integrated into Robwork project. All the image recognition function are in the file `marker1.cpp`. For proper tracking of multiple points, it was necessary to sort the detected points in consistent order for every detection.

After performing of several tests we have found, that recognition time varies among different machines. Average time for one of our computer was around 30 ms whereas on the second one it was just around 25 ms.

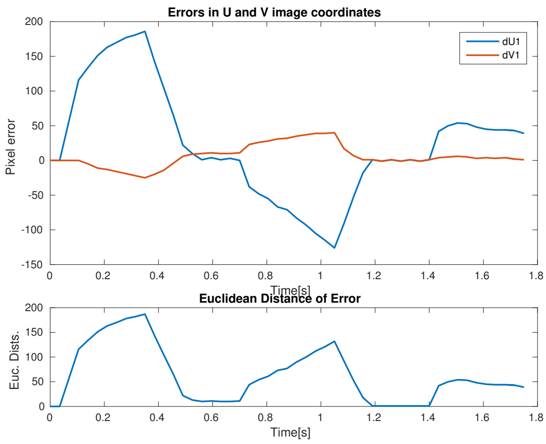
For further plots we have chosen one `deltaT` which don't cause any problems during following. And the second one, which is too short and unsaturated joints velocities are larger than limits.



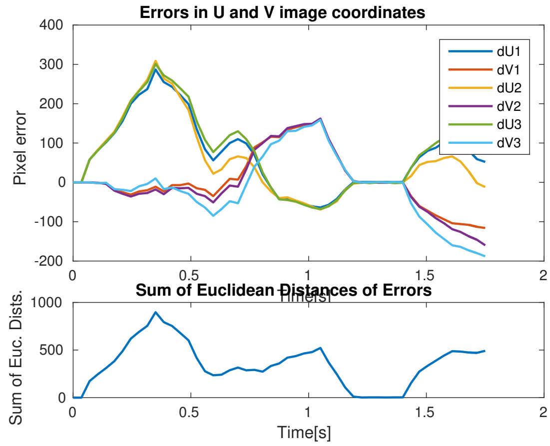
(a) Tracking Single Point

(b) Tracking 3 Points

Figure 13: Slow Sequence, `deltaT = 50 ms`



(a) Tracking Single Point

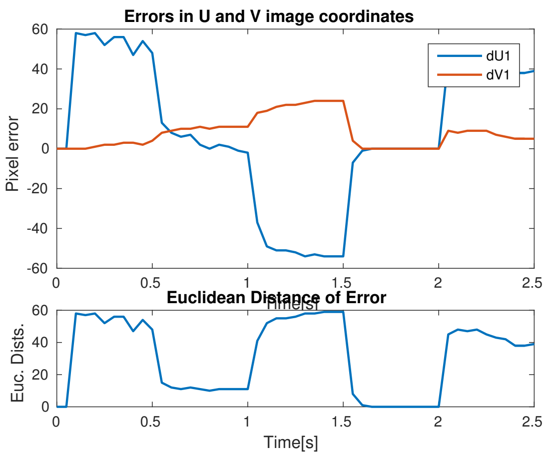


(b) Tracking 3 Points

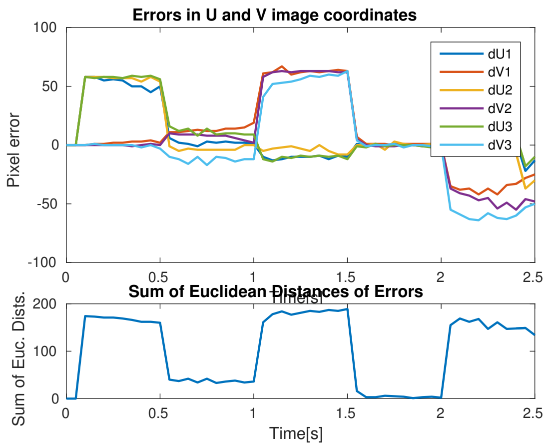
Figure 14: Slow Sequence, `deltaT = 35` ms

It is possible to see, that tracking error is generally larger on the figure 14 than on the 13. The reason is that the velocity limits were violated several times for `deltaT` = 35 ms. Another interesting find out about errors is the shape of the errors in the figure 13. The error signal shapes rectangular function. The error is larger during following the linear movement of the marker than during rotational times.

Similar reasoning applies also for marker Medium sequence on the figures 15 and 16.



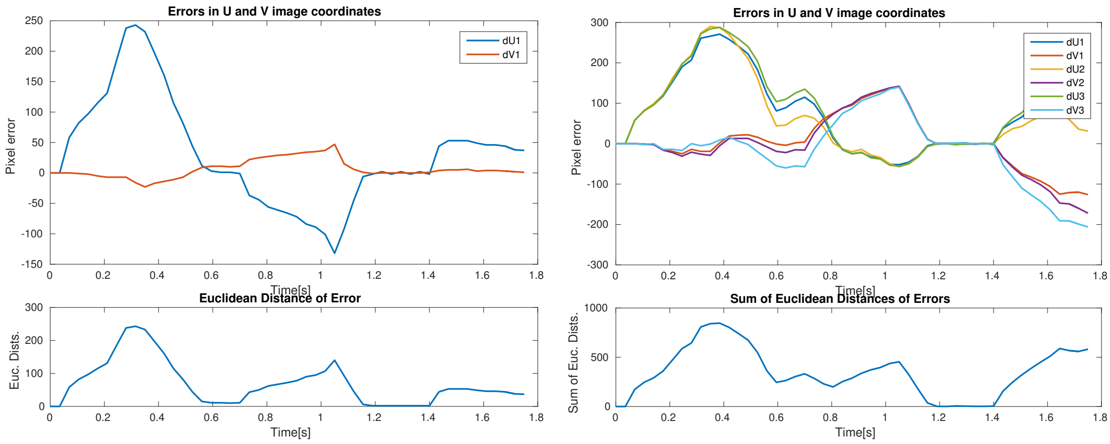
(a) Tracking Single Point



(b) Tracking 3 Points

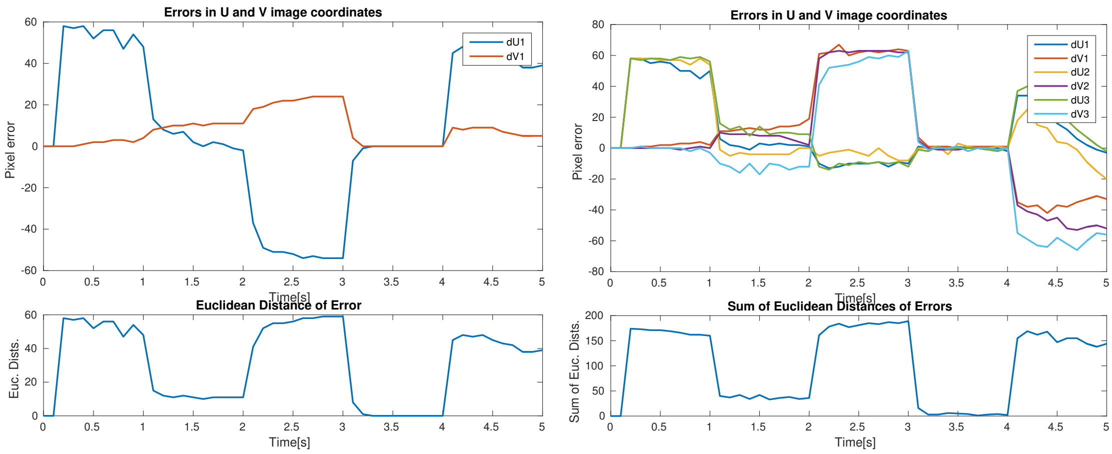
Figure 15: Medium Sequence, `deltaT = 50` ms

Finally simulation for Fast sequence are plotted on the 17 and 18.



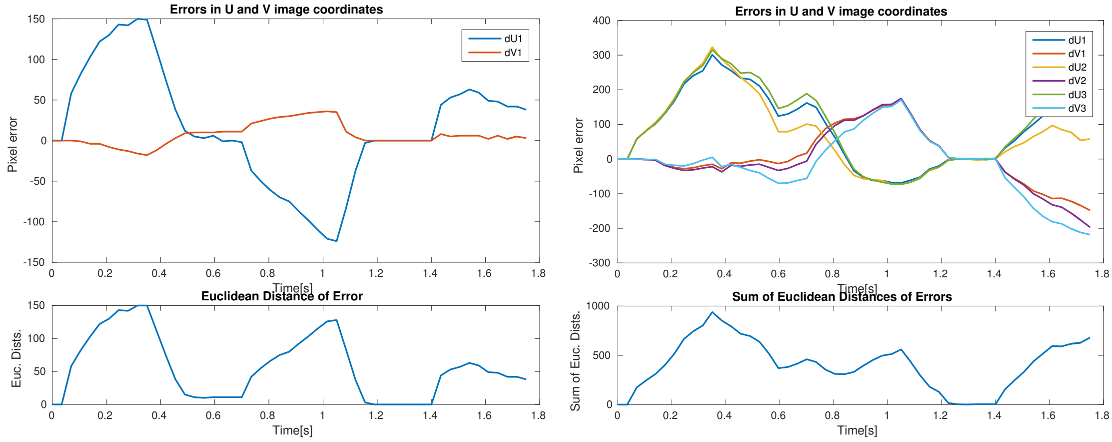
(a) Tracking Single Point (b) Tracking 3 Points

Figure 16: Medium Sequence, `deltaT = 35` ms



(a) Tracking Single Point (b) Tracking 3 Points

Figure 17: Fast Sequence, `deltaT = 100` ms



(a) Tracking Single Point

(b) Tracking 3 Points

Figure 18: Fast Sequence, `deltaT = 35` ms

Scaled joint positions and velocities