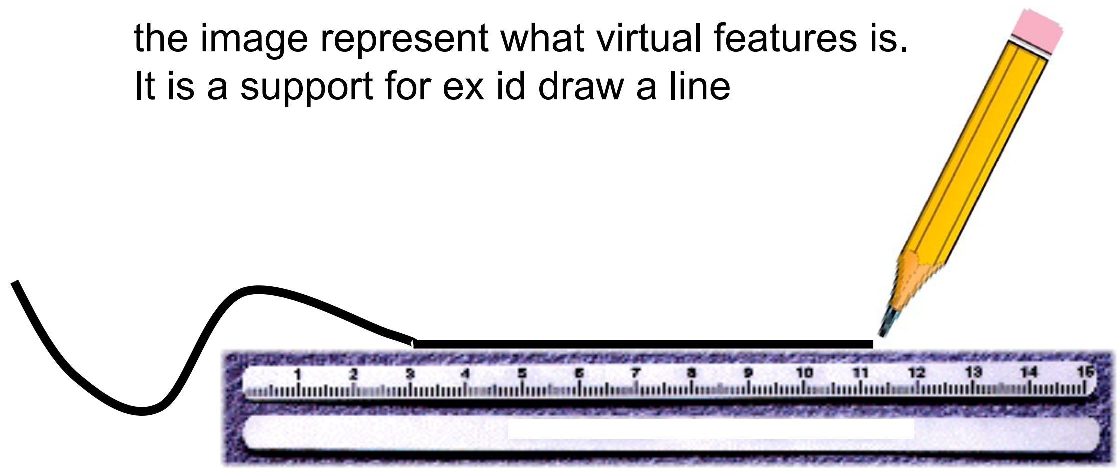
Medical Robotics

Marilena Vendittelli

Virtual Fixtures

Sapienza
Università di Roma

the image represent what virtual features is.
It is a support for ex id draw a line



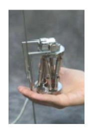
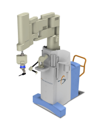
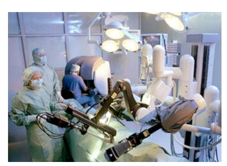
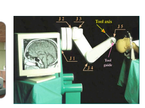
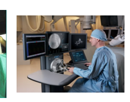
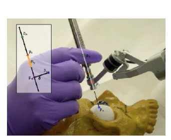
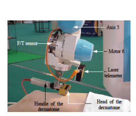
- introduced in 1992 by Rosenberg (US Air Force) in the context of telerobotic manipulation to study

  ``*the beneficial effects of corrupting the link between operator and remote environment by introducing abstract perceptual information into the interface called virtual fixtures*''

VIRTUAL FIXTURE in someway manipulate intentional motion or, in case of teleoperation, they transmit motion from the surgeon(or how manipulate the robot), to what actuate the motions.

- an alternative to force feedback from the environment providing physical constraints useful to improve safety, accuracy, and speed of robot-assisted manipulation tasks

- can be applied to both cooperative manipulation and telemanipulation systems

domain of use	function	kinematic architecture	control modality	sensors and actuators
orthopedics   	machining of rigid surface	conventional 5 (drill) or 6 (cut) dof	autonomous **cooperative or “hands-on”**	conventional vel: mm/s force: until 100N
MIS 	constrained manipulation	RCM 5 or 6 external + extra internal dof	teleoperation **shared control**	conventional vel: cm/sec (high acceleration in case of beating hearth surg) force: few N
neurosurgery, int. radiology, radiotherapy   	constrained targeting	conventional + front-end with dedicated architecture	teleoperation (semi)-autonomous	MR/CT compatible (pneumatic, ultrasonic) force: few N insertion (usually) manual (undetermined in case
microsurgery  	micromanipulation	dedicated kinematic architecture	**shared/cooperative** teleoperation	piezo, ultrasonic actuators force: few mN vel: 0.70m/s (manual procedure)
tele-echo, TMS, skin harvesting   	surface tracking	conventional + dedicated wrist architecture	autonomous teleoperation	conventional vel: mm/s force: few N

- two main types

ex. of the ruler.

  - Guidance Virtual Fixtures (GVFs) which assist the user in moving the manipulator along the desired paths or surfaces in the workspace

  - Forbidden-Region Virtual Fixtures (FRVFs) which prevent the manipulator from entering into the forbidden regions of the workspace

- force/motion relationships can be of either admittance or impedence type for both categories of VF (see later)

when you implement these virtual features, that imply an interaction between the user and the robot, you can model this interaction in 2 main ways: you can use either ADMITTANCE or IMPEDENCE for ex. a simple mass

admittance-type GVFs: $V(s) = Y(s)F(s)$(linear device)

- in general, the admittance $Y(s)$ is chosen differently in different Cartesian directions

- by filtering the applied force components in the non-preferred directions, a passive guidance is created along the preferred direction of motion

- varying response in non-preferred force components creates different guidance levels

  - *hard guidance*: none or almost none of the non-preferred force component is permitted, leaving the user with no or little freedom to deviate from the preferred (planned) path

  - *soft guidance*: give the user the freedom to move away from the path by allowing some motion in the non-preferred directions

    we can deviate a little bit from the planned path

experiments in microsurgical environments with an admittance-controlled cooperative robot have demonstrated that operators will perform best in uncertain environments with a *medium-level* GVF because the VF planner is not perfect impedance-type GVFs: $F(s) = Z(s)V(s)$(linear device)

- in general, the impedance $Z(s)$ is chosen differently in different Cartesian directions

- act as potential fields, actively influencing the motion of the robotic manipulator

SKIP

admittance-type FRVFs

- FRVFs are actually a subclass of GVFs for admittance-controlled cooperative robots (see the Acrobot control)
- in telemanipulation, we are principally concerned with the penetration of the slave manipulator into the forbidden region; penetration of the master device into the corresponding region of its workspace has no consequences

impedance-type FRVFs

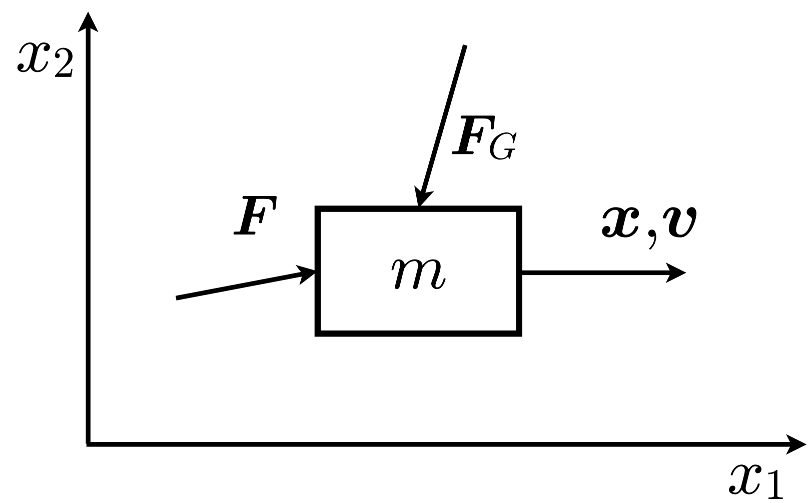
- can be implemented on telemanipulators by overlaying a penalty-based virtual wall on the existing telemanipulation controller
- it is possible to implement the virtual wall on either the master or the slave side (or simultaneously on both); both have the effect of reducing movement of the slave into the forbidden region
- each presents a different haptic experience for the user, depending on the underlying telemanipulation controller

Example 1: a simple linear system

Assuming we have a mass which is translated in the plan. There is a control on its move(imagine a structure of a mobile robot.) So you have a force that moves around but this is also subjected to the external force which is the interaction force.

control based on admittance and impedance type virtual fixtures for a mass m translating on the plane under the action of the control force $\boldsymbol{F}$ and the guiding force $\boldsymbol{F}_G$ (e.g., force due to the interaction with a surgeon) without friction

To model the motion of this mass we use cartesian coordinates of the center of mass(CoM), and the derivative builds the velocity in cartesian space.



$$\boldsymbol{x} = (x_1,\ x_2)^T$$

$$\boldsymbol{v} = (\dot{x}_1,\ \dot{x}_2)^T$$

$$m\dot{\boldsymbol{v}} = \boldsymbol{F} + \boldsymbol{F}_G$$

- admittance-based control

  the admittance filters the force that is the interaction force between tthe operator and robot, in this case it is just a mass. This force is filtered in according to this admittance to provide a reference velocity for the system.

  - from an admittance-type GVF

$$\boldsymbol{V}(s) = \boldsymbol{Y}(s)\boldsymbol{F}_G(s)$$

  - choosing
    - the desired mass velocity $\boldsymbol{V}_d(s) = \boldsymbol{V}(s)$

      integral of vd(reference velocity)

      elastic component proportional to the position error

    - the control input $\boldsymbol{F} = m\dot{\boldsymbol{v}}_d + \boldsymbol{K}_D(\boldsymbol{v}_d - \boldsymbol{v}) + \boldsymbol{K}_P(\boldsymbol{x}_d - \boldsymbol{x})$

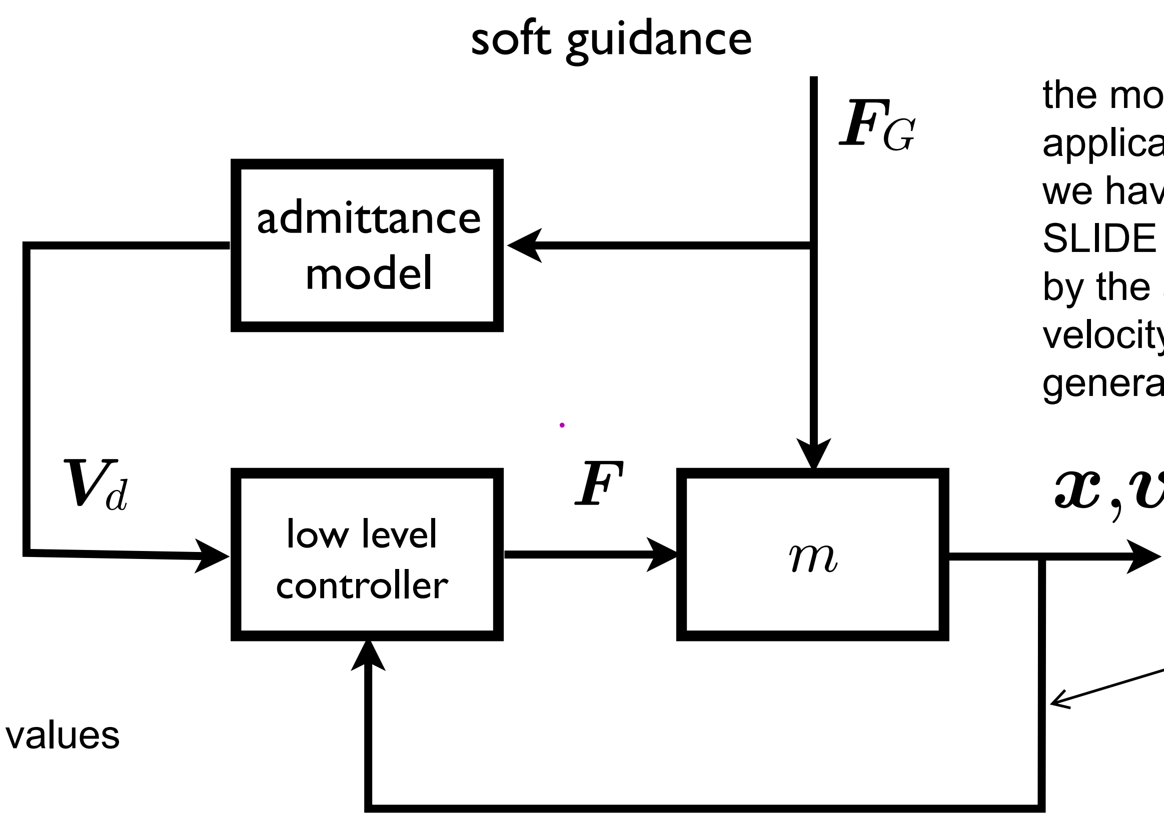
      inertia component

      friction component proportional to the velocity error

  - the system will move according to the designed admittance $\boldsymbol{Y}(s)$

Example 1: admittance-based control schemes

Here we see which is the control scheme that corresponds to the law illustrated



the motion of the mass is the result of the application of 2 forces F(interaction force that we have choosen to be equal to equation in SLIDE 8) and Fg(guidded force that is filtered by the admittance). This provides the reference velocity Vd for the low level control, and this generates F.

feedback for the low level control

the components of the velocity are scaled values of the components of the force

admittance matrix

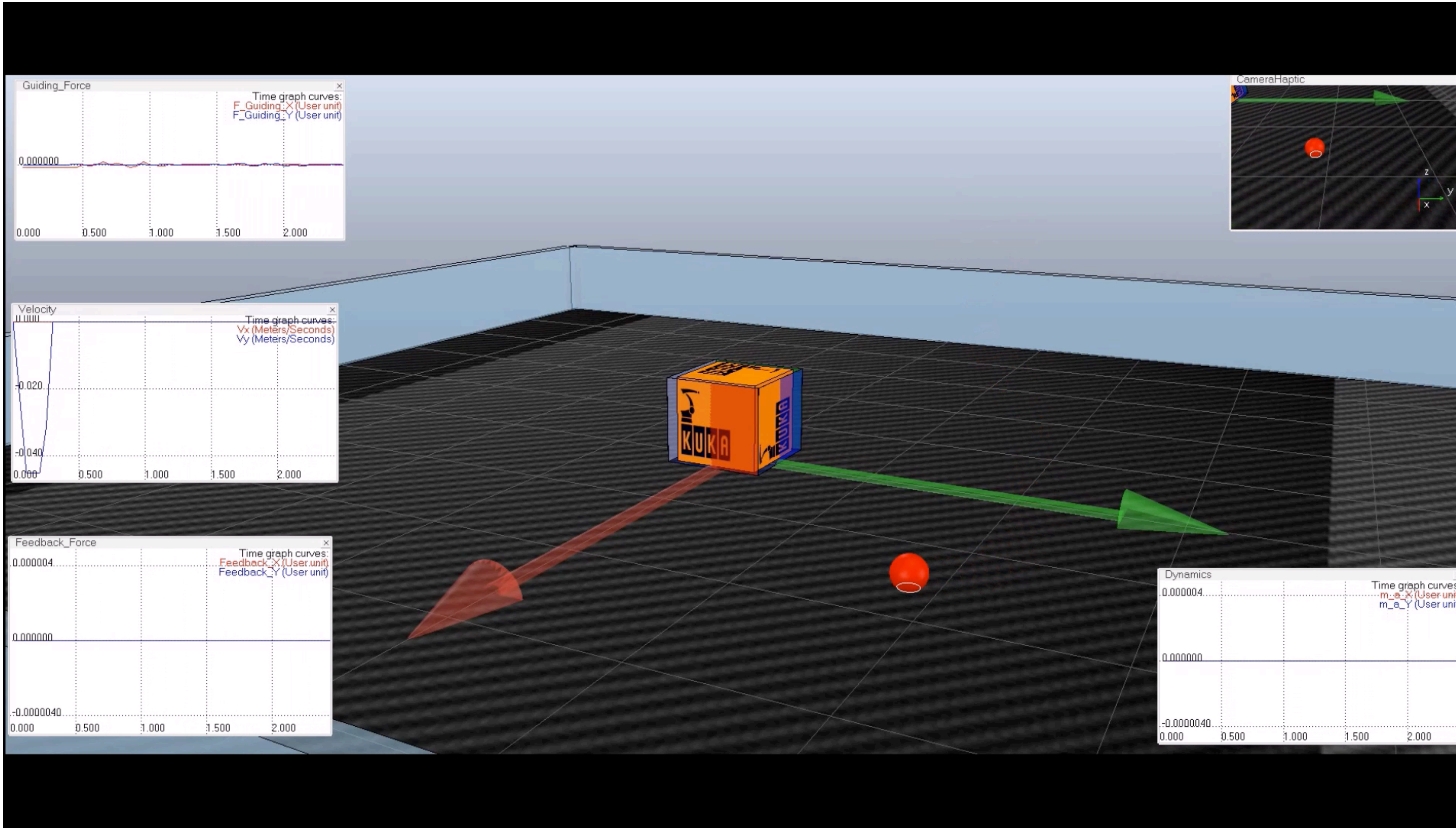
$$\begin{bmatrix} \dot{x}_d \\ \dot{y}_d \end{bmatrix} = \begin{bmatrix} k_{a,x} & 0 \\ 0 & k_{a,y} \end{bmatrix} \begin{bmatrix} F_{G,x} \\ F_{G,y} \end{bmatrix} = Y \begin{bmatrix} F_{G,x} \\ F_{G,y} \end{bmatrix}$$

If we want an orizontal movement along x direction, we have no deviation so we can choose that Ka,y will be zero or we can choose a big gain for Ka,x and a small gain for Ka,y.

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = m \begin{bmatrix} \ddot{x}_d \\ \ddot{y}_d \end{bmatrix} + \begin{bmatrix} k_{v,x} & 0 \\ 0 & k_{v,y} \end{bmatrix} \begin{bmatrix} \dot{x}_d - \dot{x} \\ \dot{y}_d - \dot{y} \end{bmatrix} + \begin{bmatrix} k_{p,x} & 0 \\ 0 & k_{p,y} \end{bmatrix} \begin{bmatrix} x_d - x \\ y_d - y \end{bmatrix}$$

admittance-based control schemes

soft guidance

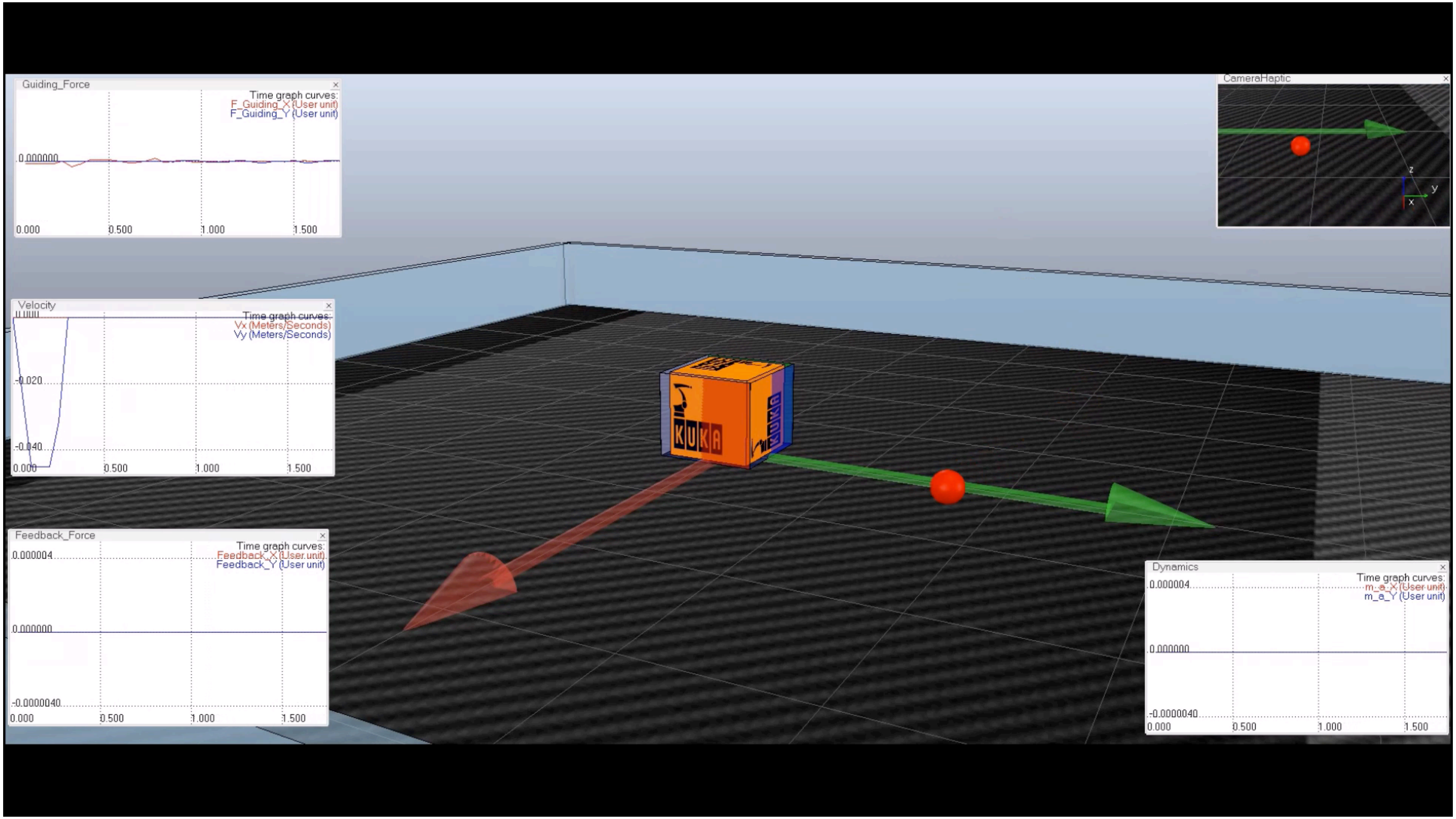


students project: Carlesimo, Chiariello, Corvini, Massimiani

admittance-based control schemes

hard guidance

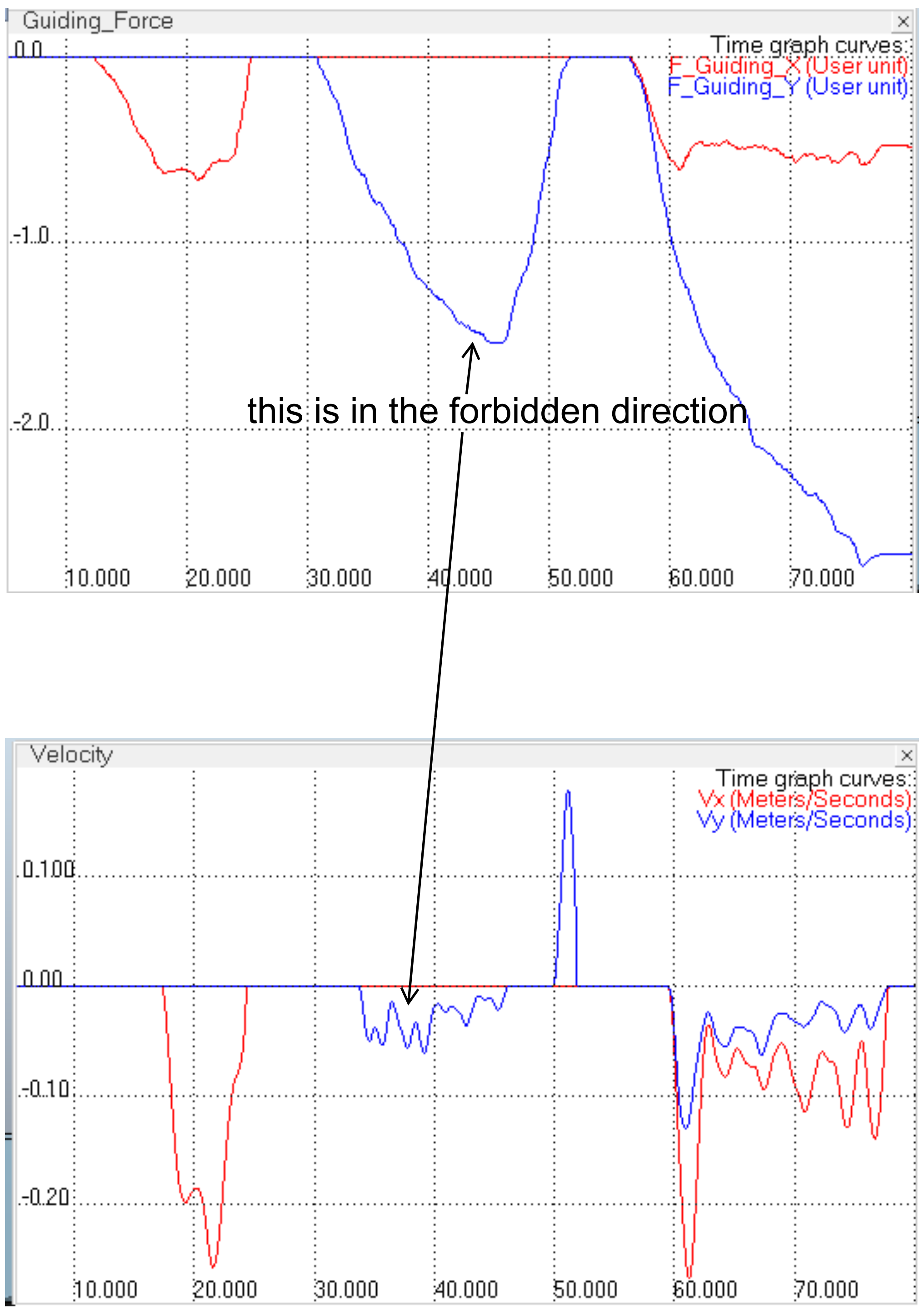
the gain assigned is higher than soft guidance



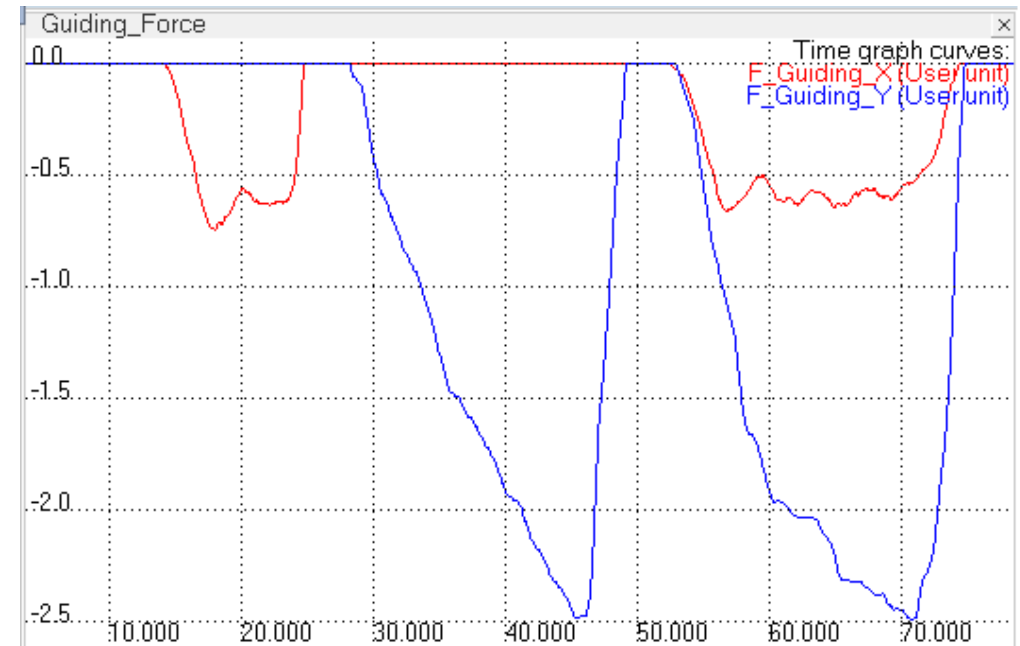
students project: Carlesimo, Chiariello, Corvini, Massimiani

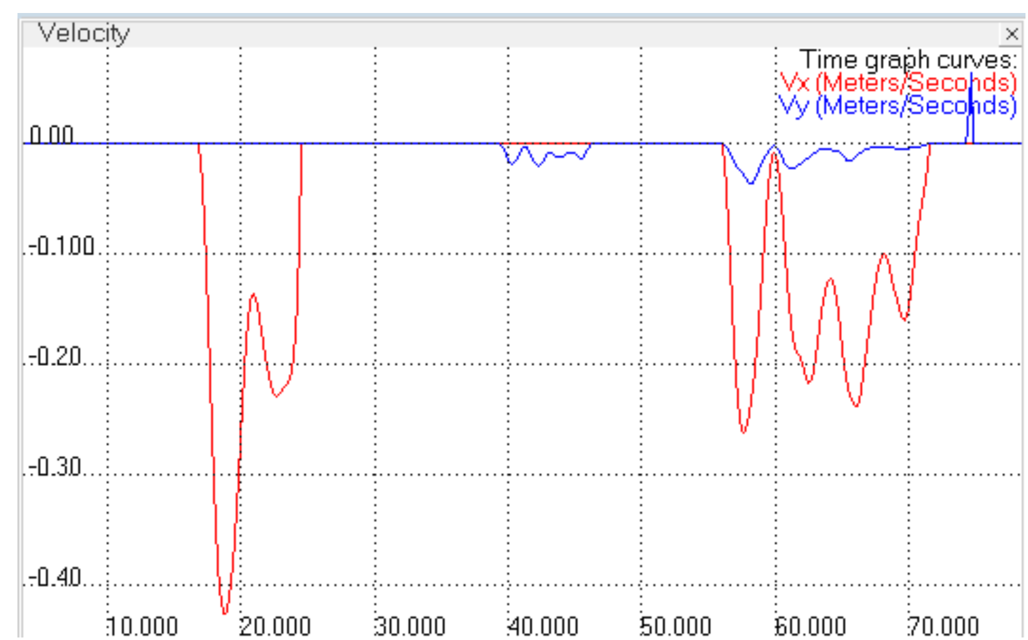
soft vs hard guidance

soft



hard



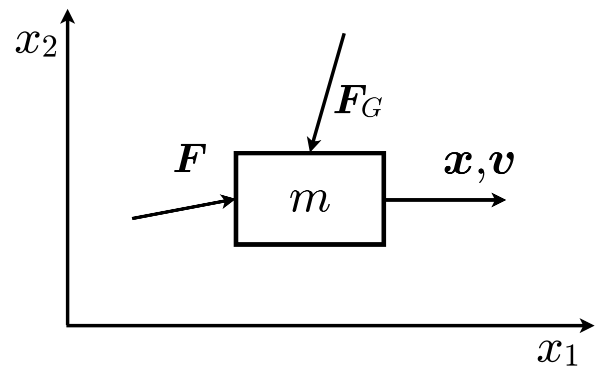


students project: Carlesimo, Chiariello, Corvini, Massimiani

the task is the same but the way to reach it is different

Example 1: a simple linear system (cont'd)

Here, the idea is that we want to design F is such a way that the interaction force is the impedance type



$$\boldsymbol{x} = (x_1,\ x_2)^T$$
$$\boldsymbol{v} = (\dot{x}_1,\ \dot{x}_2)^T$$
$$m\dot{\boldsymbol{v}} = \boldsymbol{F} + \boldsymbol{F}_G$$

- impedance-based control

The idea is to obtain for this interaction force a model of impedance that will be of the visco-elastic type

  - in this case the control $\boldsymbol{F}$ must be designed so that the mass m, under the action of the guiding force $\boldsymbol{F}_G$, matches the behavior of the impedance model provided by the impedance type GVF

$$\boldsymbol{F}_G(s) = \boldsymbol{Z}(s)\boldsymbol{V}(s)$$

  - the impedance model may be characterized by a desired, apparent, mass m_d, desired damping $\boldsymbol{K}_D > 0$ and stiffness $\boldsymbol{K}_P > 0$ with respect to a motion reference $\boldsymbol{x}_d$

this desired mass is the perceived mass

$$m_d(\dot{\boldsymbol{v}} - \dot{\boldsymbol{v}}_d) + \boldsymbol{K}_D(\boldsymbol{v} - \boldsymbol{v}_d) + \boldsymbol{K}_P(\boldsymbol{x} - \boldsymbol{x}_d) = \boldsymbol{F}_G$$

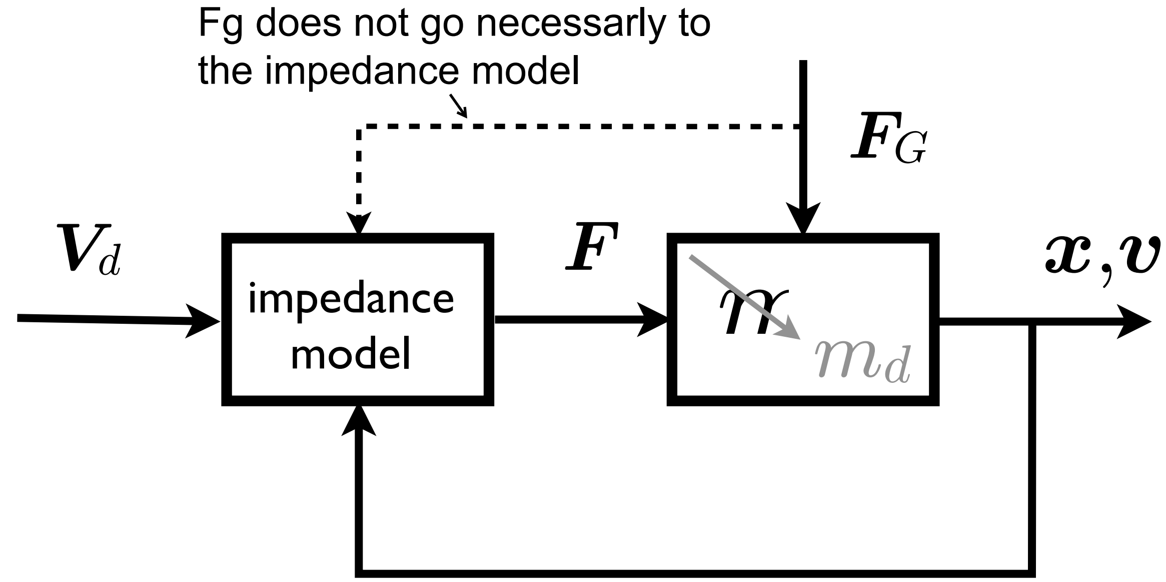
the point is how to obtain this interaction force

  - this is obtained through the control

$$\boldsymbol{F} = \frac{m}{m_d}\left(m_d\dot{\boldsymbol{v}}_d + \boldsymbol{K}_D(\boldsymbol{v}_d - \boldsymbol{v}) + \boldsymbol{K}_P(\boldsymbol{x}_d - \boldsymbol{x})\right) + \left(\frac{m}{m_d} - 1\right)\boldsymbol{F}_G$$

where a measure of $\boldsymbol{F}_G$ is not needed if $m_d = m$ (compliance control)

Example 1: a simple linear system (cont'd)



$$\begin{bmatrix} x_d(t) \\ y_d(t) \end{bmatrix} = \begin{bmatrix} A_x sin(\omega_x t) \\ A_y sin(\omega_y t) \end{bmatrix}$$ reference motion (task)

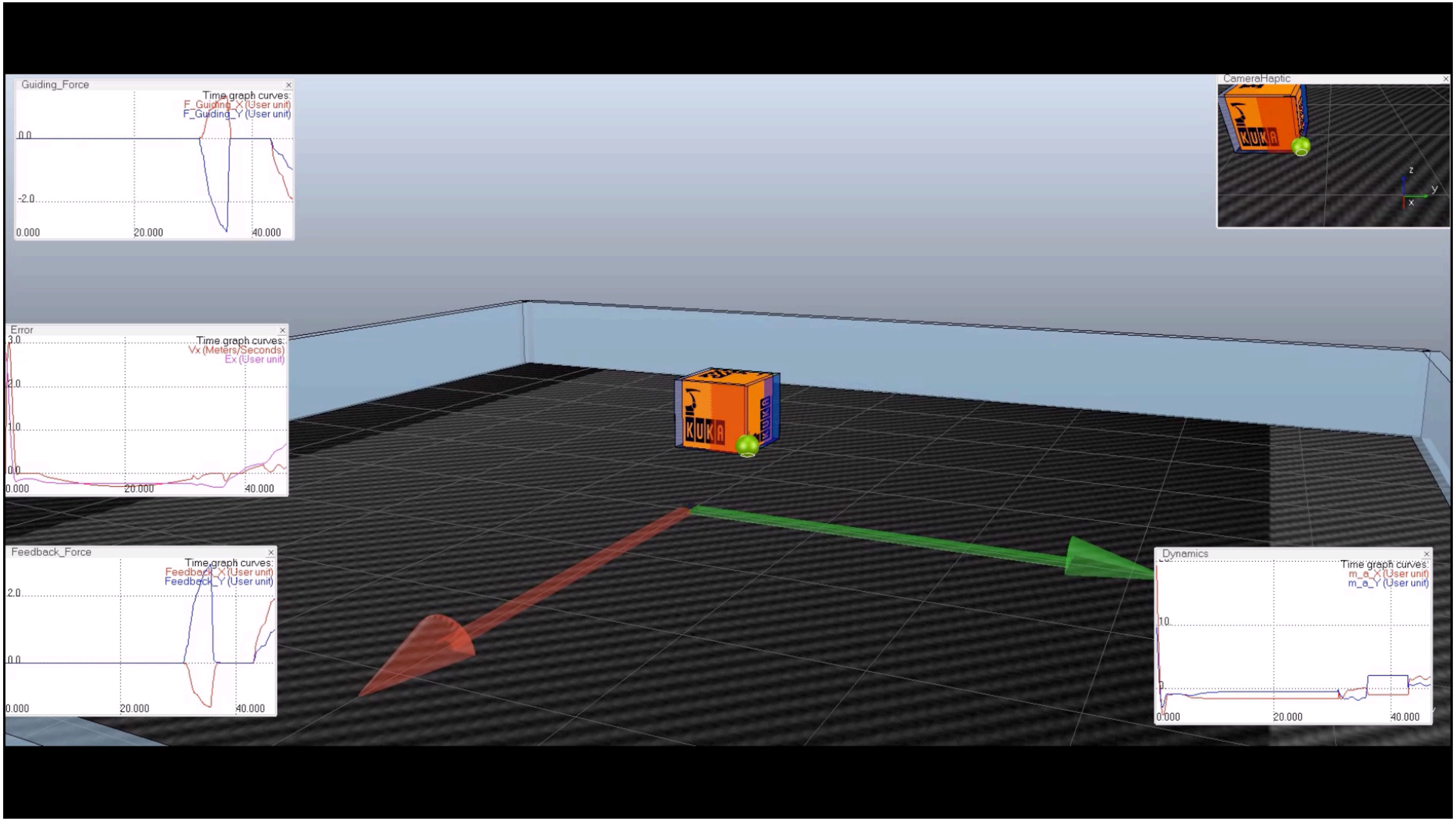
$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \frac{m}{m_d}\left[m_d \begin{bmatrix} \ddot{x}_d \\ \ddot{y}_d \end{bmatrix} + \begin{bmatrix} k_{v,x,I} & 0 \\ 0 & k_{v,y,I} \end{bmatrix} \begin{bmatrix} \dot{x}_d - \dot{x} \\ \dot{y}_d - \dot{y} \end{bmatrix} + \begin{bmatrix} k_{p,x,I} & 0 \\ 0 & k_{p,y,I} \end{bmatrix} \begin{bmatrix} x_d - x \\ y_d - y \end{bmatrix} \right] + \left(\frac{m}{m_d} - 1 \right) \begin{bmatrix} F_{G,x} \\ F_{G,y} \end{bmatrix}$$

$\frac{m}{m_d}$ determines the inertia perceived by the user (lower for smaller ratio values)

impedance-based control schemes

hard guidance

low stiffness and md that is lower to the real.

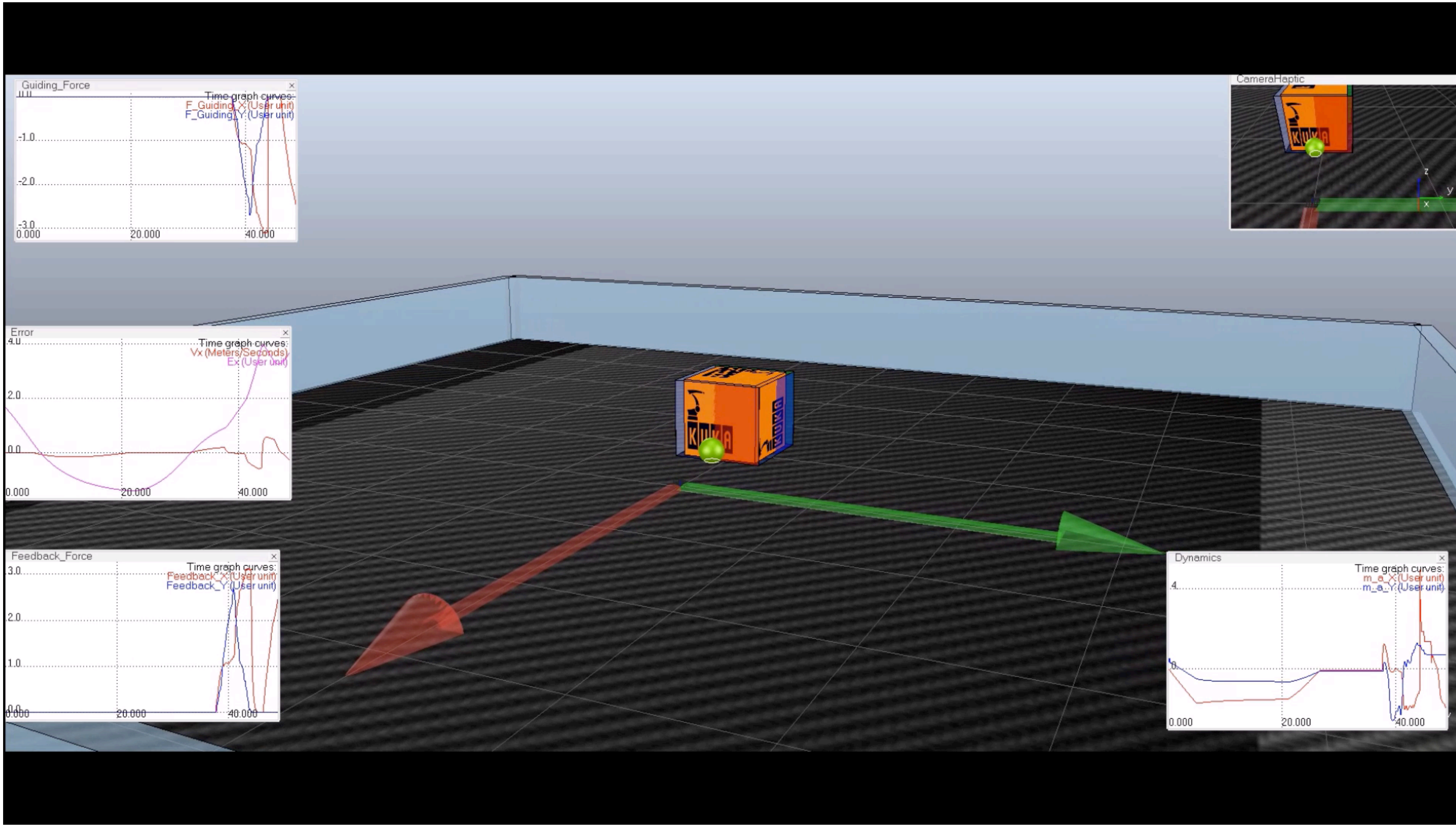


students project: Carlesimo, Chiariello, Corvini, Massimiani

impedance-based control schemes

soft guidance

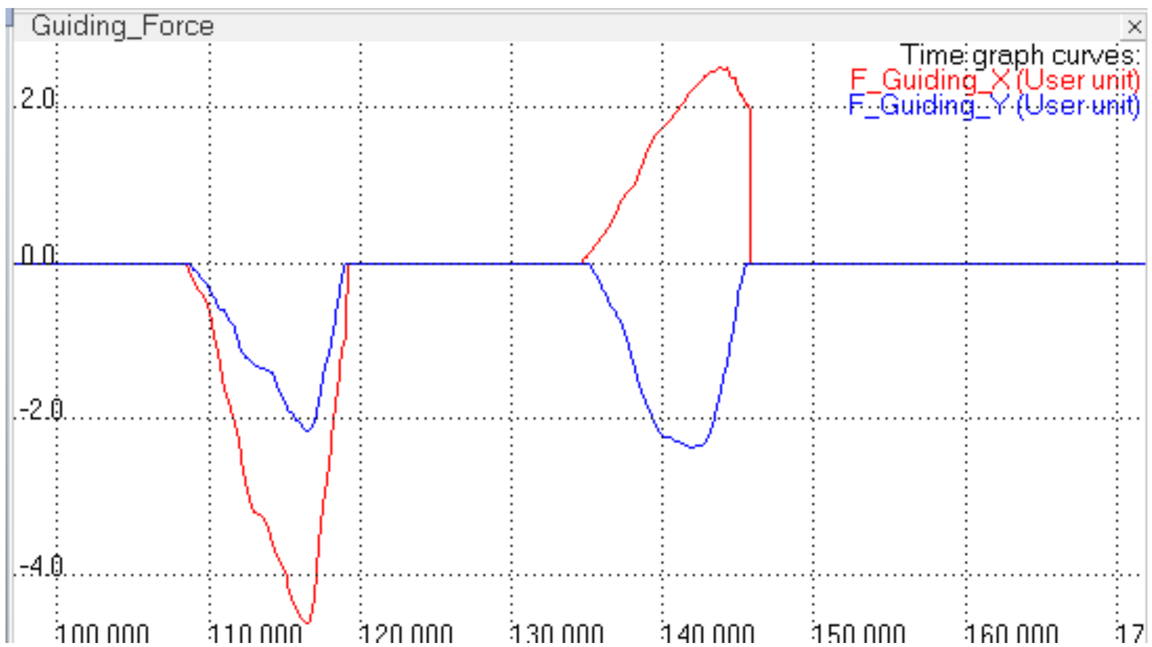
higher stiffness and md is higher

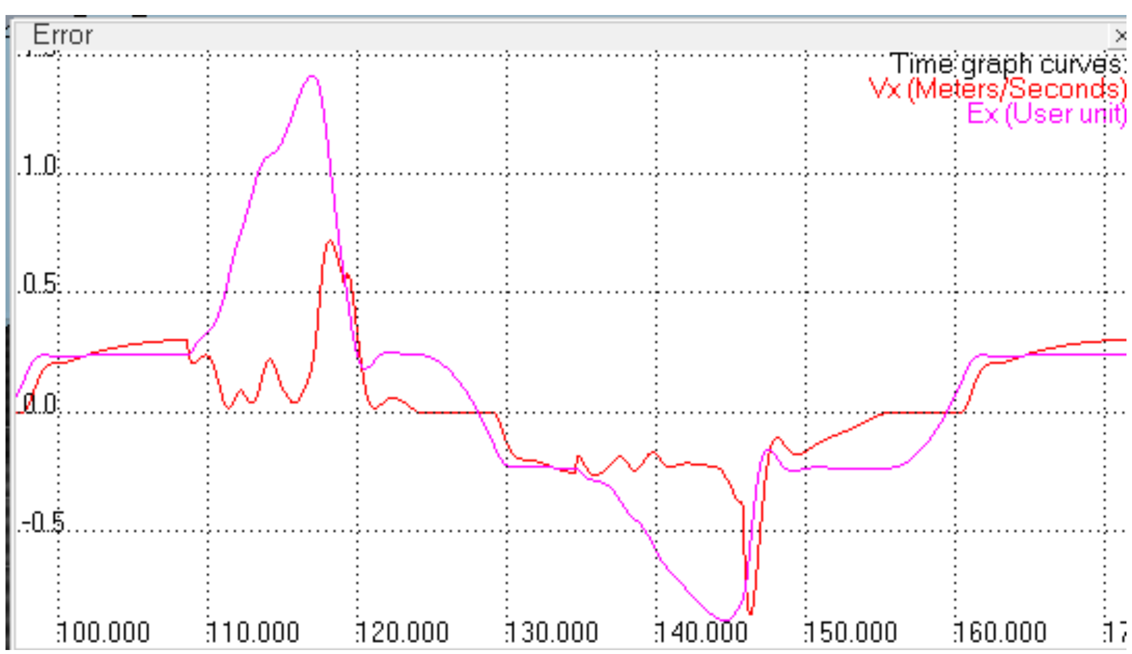


students project: Carlesimo, Chiariello, Corvini, Massimiani

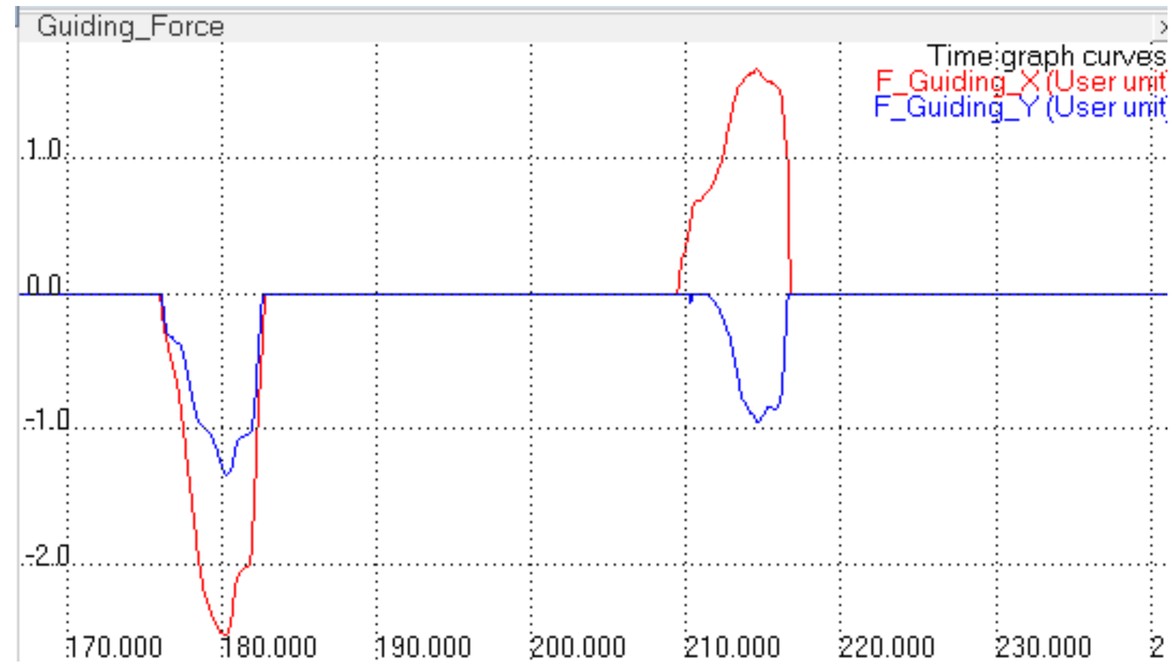
soft vs hard guidance

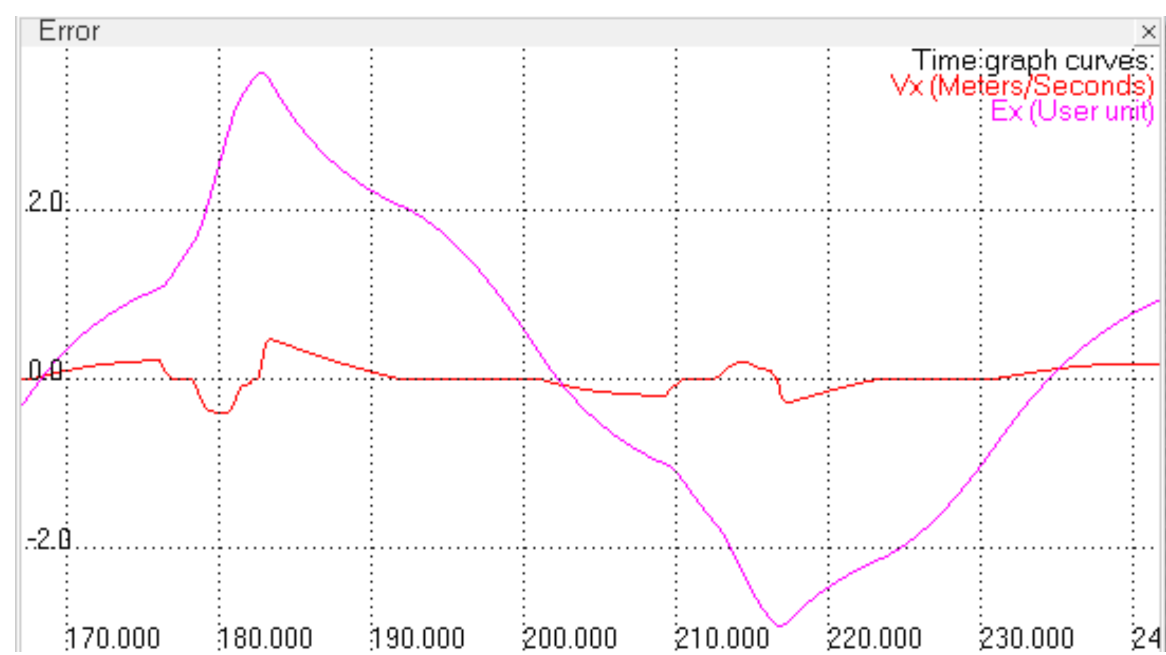
high stiffness





low stiffness



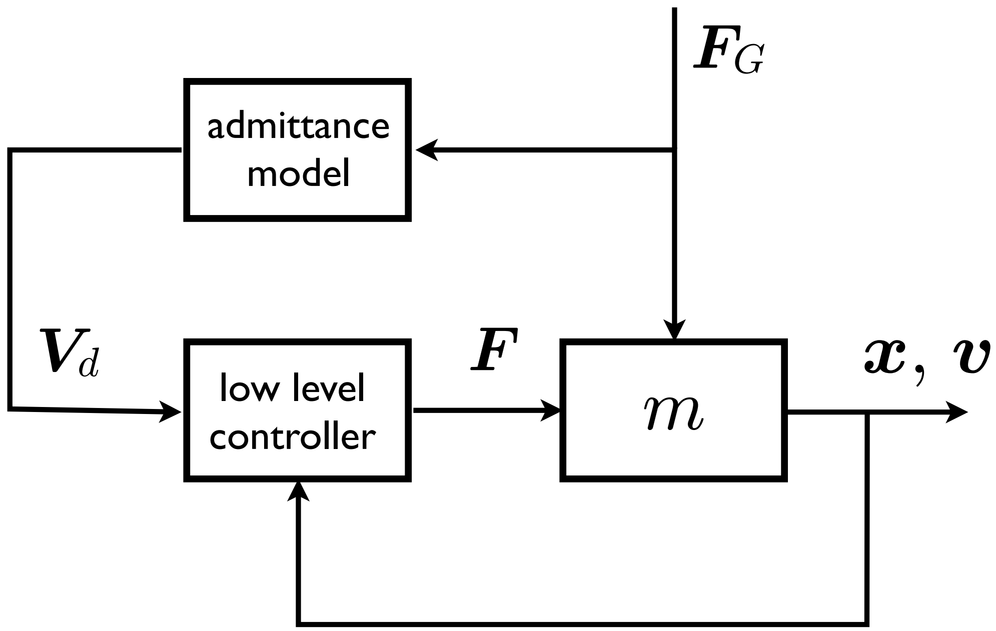


students project: Carlesimo, Chiariello, Corvini, Massimiani

control schemes comparison

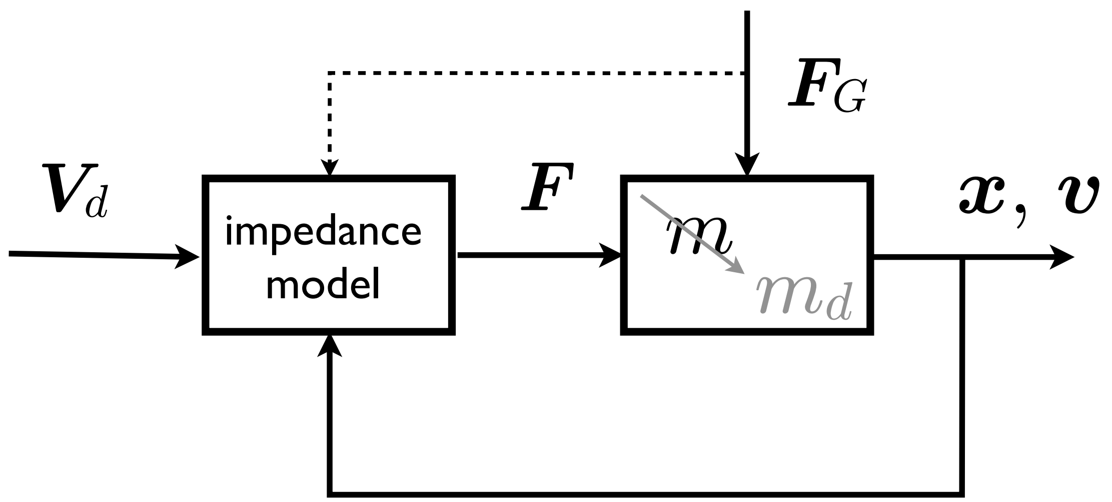
admittance-based

$$V(s) = Y(s)F_G(s)$$



impedance-based

$$F_G(s) = Z(s)V(s)$$

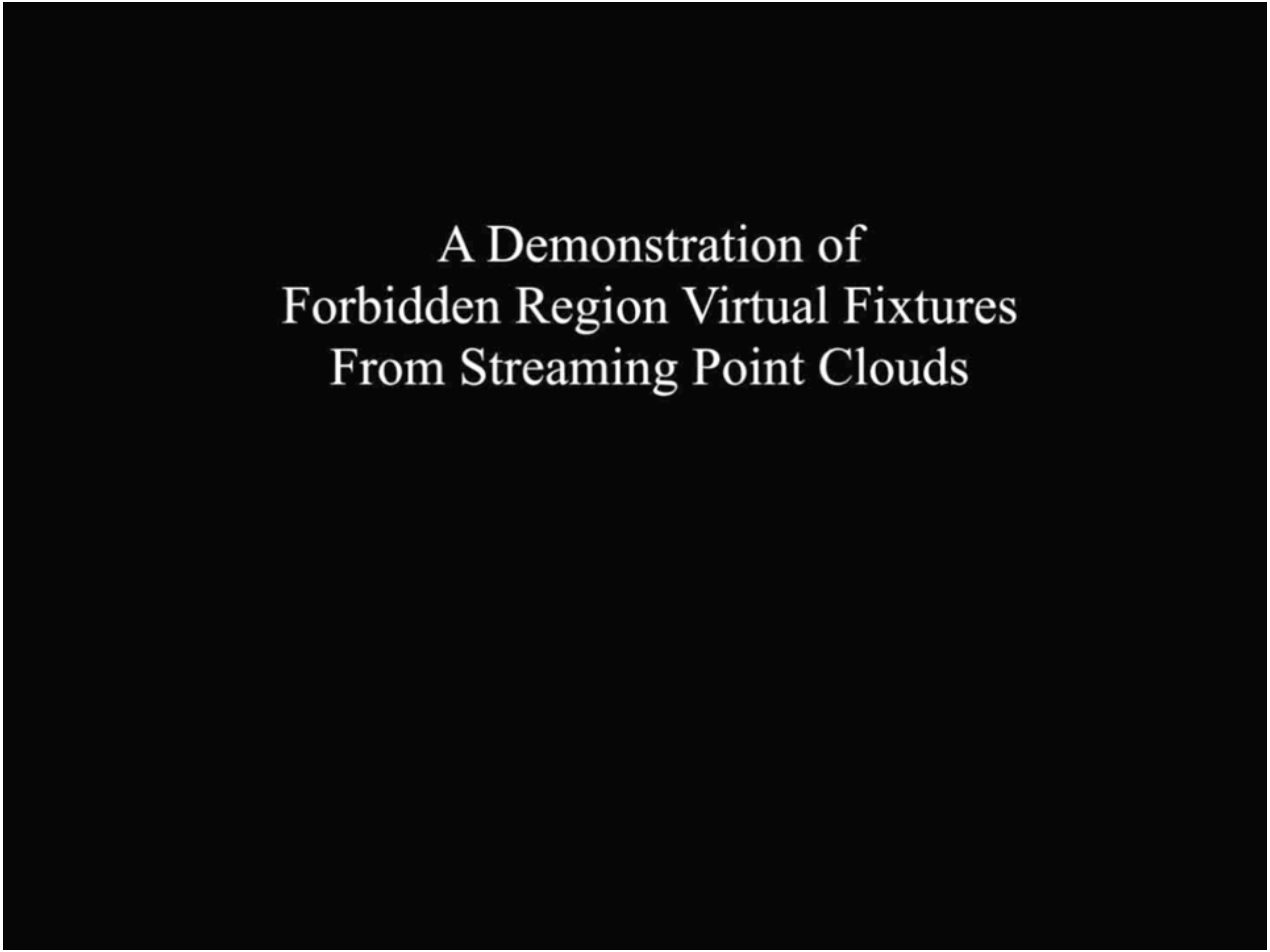


in both cases

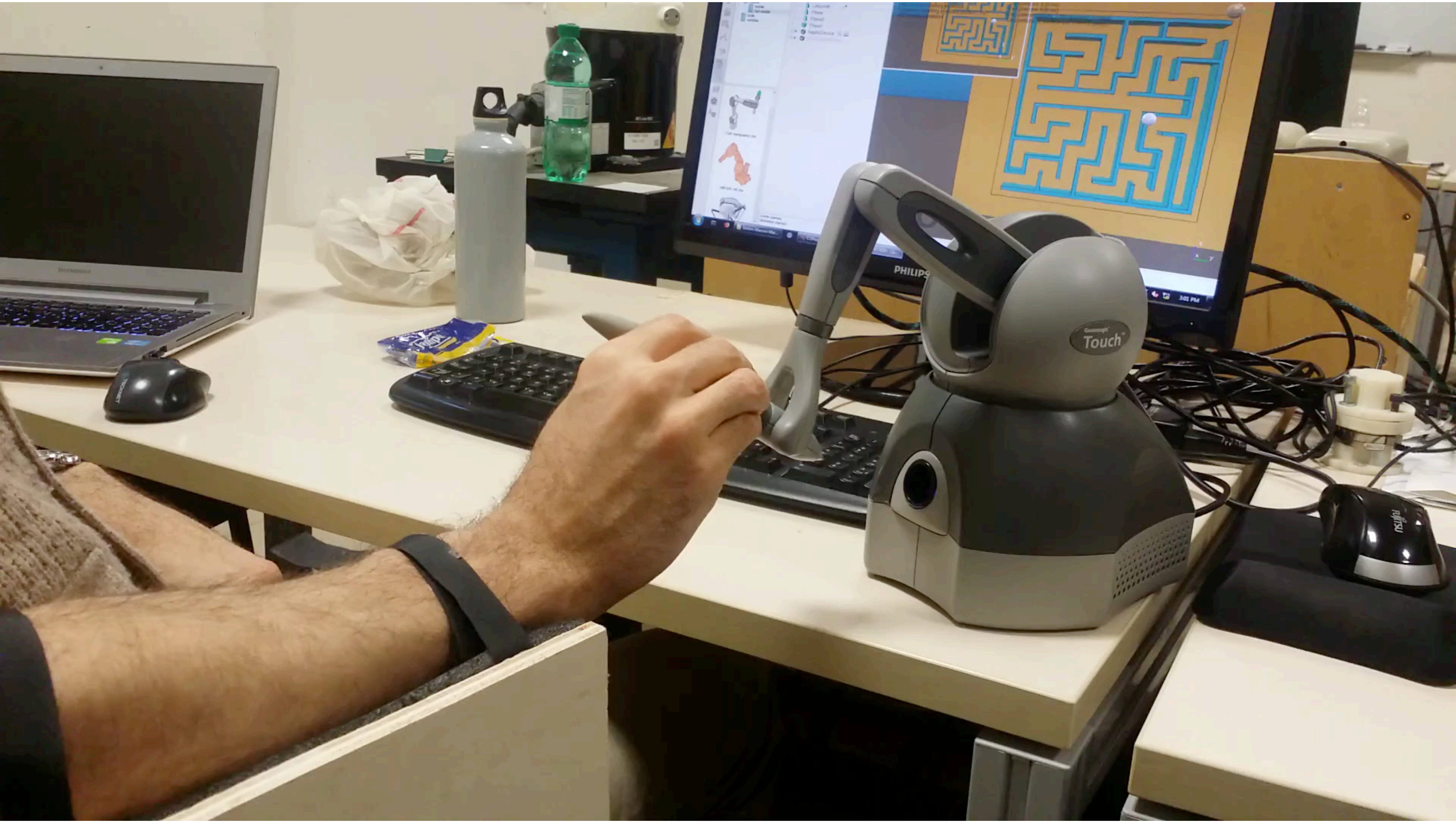
$$m(\dot{v} - \dot{v}_d) + K_D(v - v_d) + K_P(x - x_d) = F_G$$

but with different design options and different implementations

Forbidden Region VF

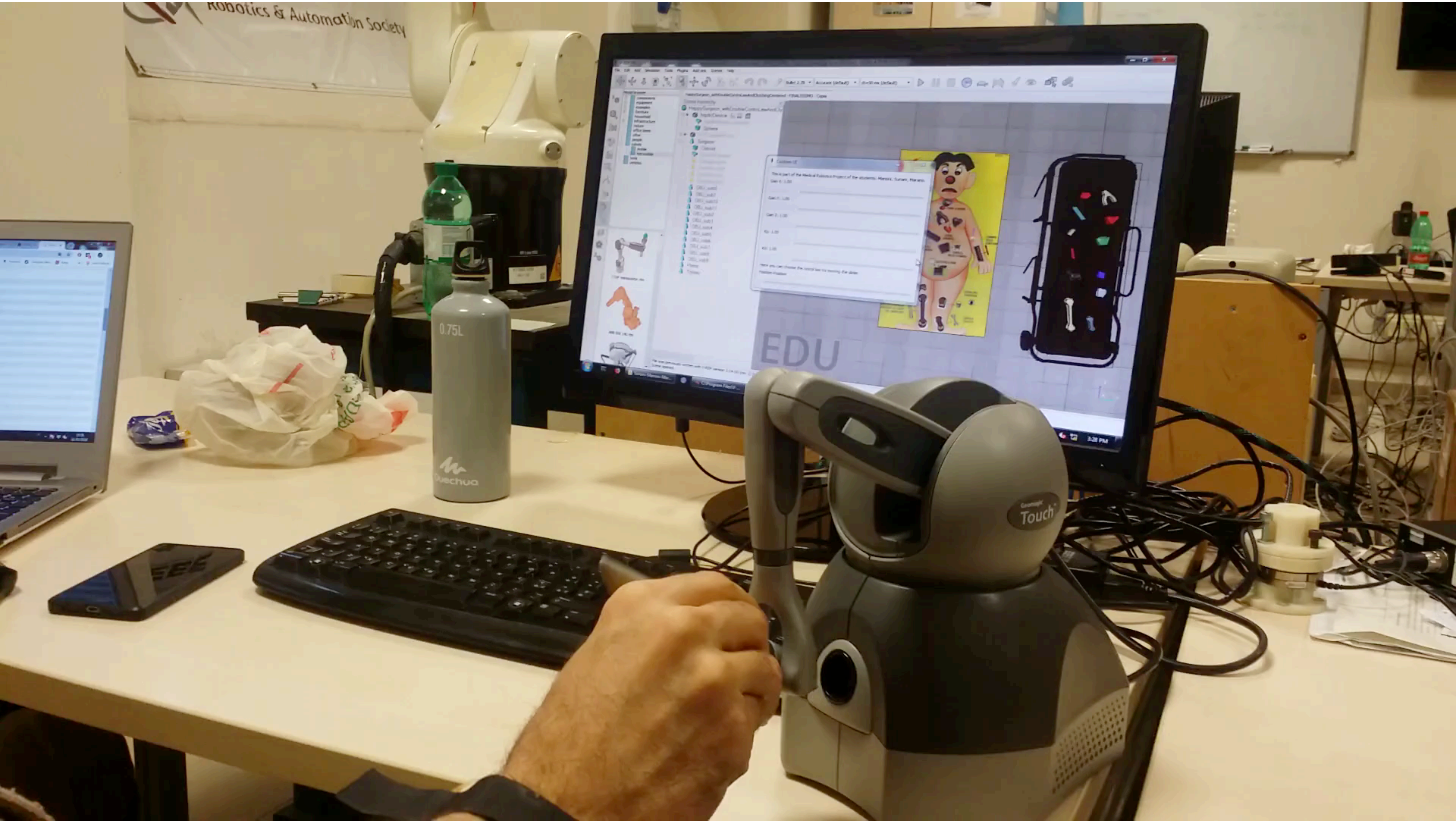


FRVF for rehabilitation



students project: Suriani, Marano, Manoni

FRVF for rehabilitation



students project: Suriani, Marano, Manoni

GVF for needle insertion

VirtualFixProj2.avi

students project: Bucci, Mancini, Planamente

bibliography

- “The Use of Virtual Fixtures As Perceptual Overlays to Enhance Operator Performance in Remote Environments,” L. B. Rosenberg, Technical Report AL-TR-0089, USAF Armstrong Laboratory, Wright-Patterson AFB OH, 1992
- Virtual fixtures: Perceptual tools for telerobotic manipulation,” L. B. Rosenberg, IEEE Virtual Reality Annual International Symposium, pp. 76-82, 1993
- “Spatial motion constraints using virtual fixtures generated by anatomy” M. Li, J. Koo, M. Ishii, R.H. Taylor, IEEE Transations on Robotics, vol. 23, no. 1, pp. 4-19, 2007
- “Surgical and interventional robotics: Part III,” G. D. Hager, A. M. Okamura, P. Kazanzides, L. L. Whitcomb, G. Fichtinger, R. H. Taylor, IEEE Robotics and Automation Magazine, vol. 15, no. 4, pp. 84-93, 2008