DEVELOPMENT OF A SIMULATION ENVIRONMENT FOR TELEOPERATED SURGICAL TASK

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- Coupling and clutching
- Kuka Cartesian control
- Teleoperation principles
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- The simulation software
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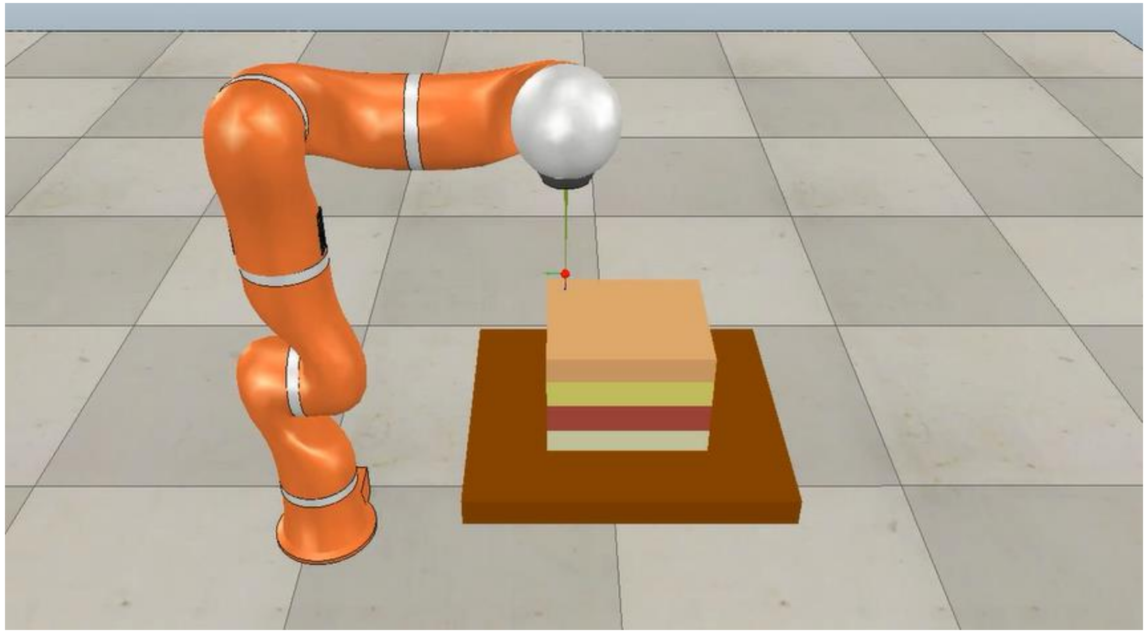
GOAL

Realization of a simulative framework for:

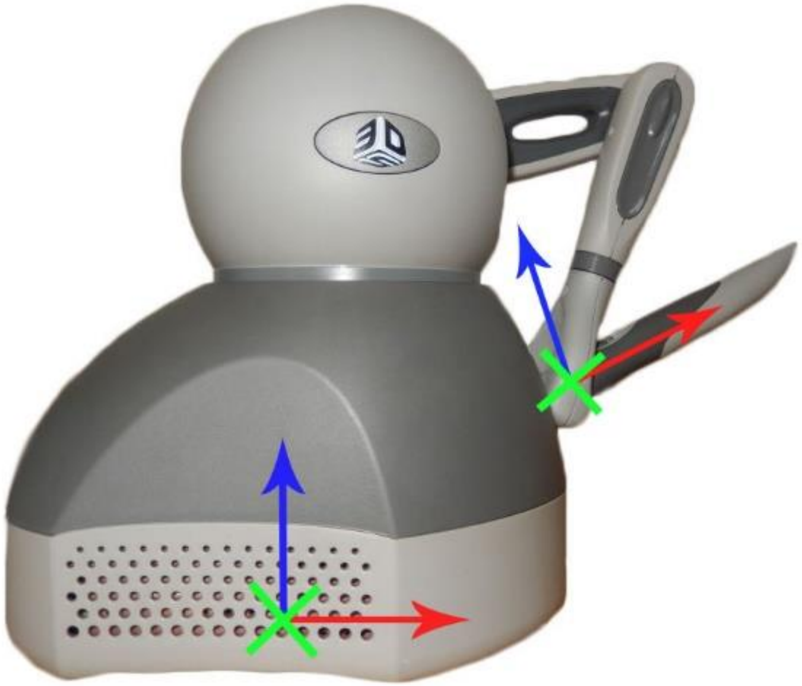
- Teleoperation task between real haptic device and virtual robot
- Needle insertion task
- Computation of haptic feedback



INTRODUCTION AND MOTIVATIONS

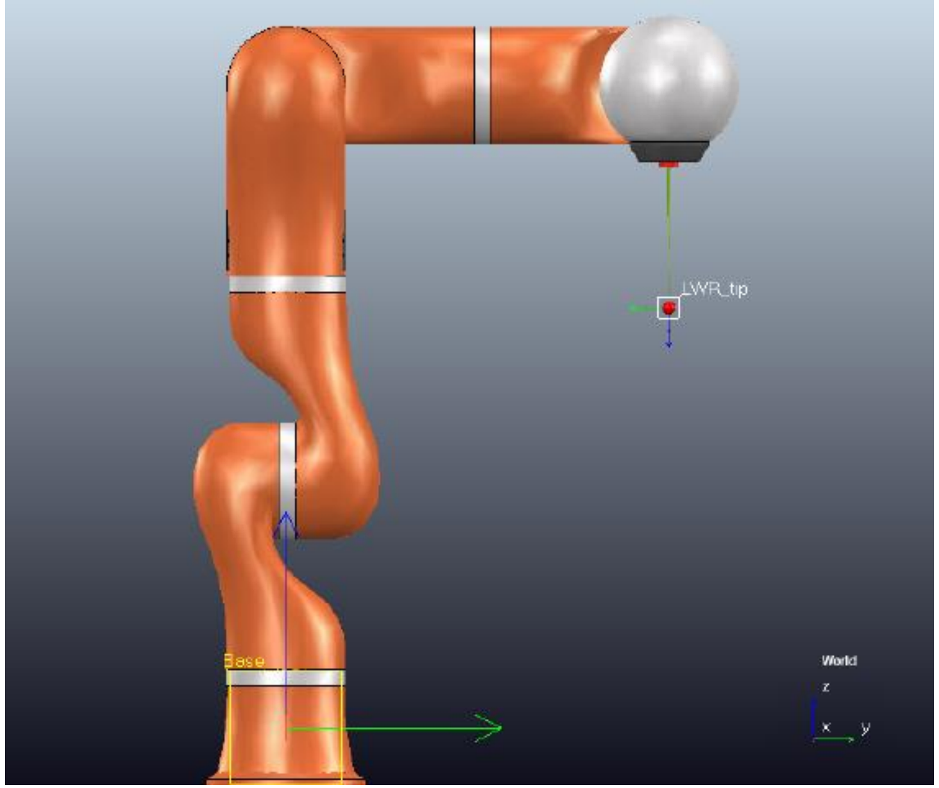
- Teleoperation = remote control
- Master in the local site, Slave in the remote site
- Motivation: command robot in far, dangerous, small/big environments
- Requirements: quality of technologies, communication channels, teleoperation schemes
- Telesurgery improves surgeon’s technical abilities (precision, dexterity, safety)
- Needle insertion: definition and applications
- Simulated needle insertion: cheap and safe
- Simulation requires needle-tissue model of interaction

Devices: Geomagic Touch



- Geomagic Touch by 3D Systems (previously Phantom Omni by SensAble Technologies)
- 6 joints: first 3 actuated, others 3 passive spherical wrist
- Small dimensions, limited workspace 160 w x 120 h x 70 d mm
- Maximum exertable linear force = 3.3N
- 2 buttons
- Ethernet connectivity
- Compatible with OpenHaptics Toolkit (3D Systems) and CHAI3D libraries.

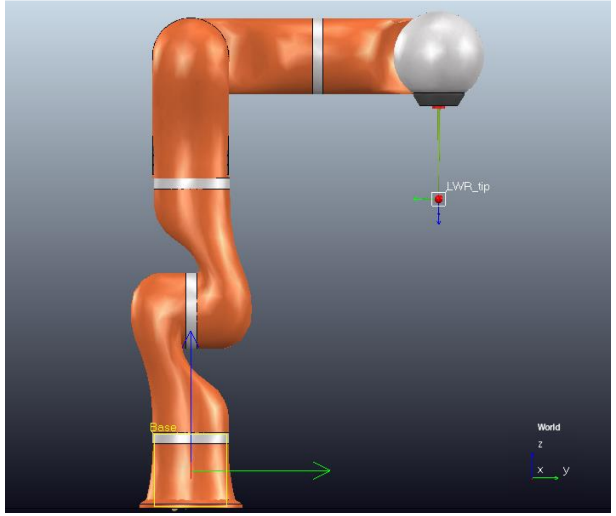
DEVICES: KUKA LWR 4+ (AKA KUKA LBR 4+)



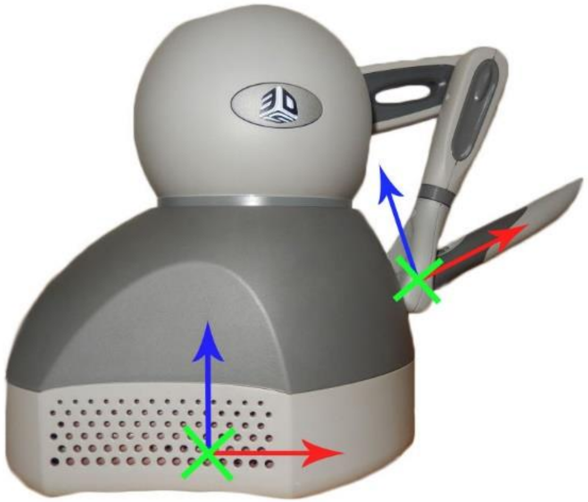
- Redundant robot, 7R, actuated, open chain
- Lightweight (16 kg), payload of 7 kg
- Used for human-robot interaction, industrial applications, research
- Low level controllers integrated in the motors: just impose desired joints positions $\boldsymbol{q}$ or velocities $\dot{\boldsymbol{q}}$
- End effector = needle (150 mm)
- Model available in VREP: geometric Jacobian, approximated physical parameters and control loops

MASTER-SLAVE FRAME MISMATCH

The frames of Geomagic Touch's end effector and KUKA's tool-tip do not coincide, so to guarantee coherent movements of the slave it is necessary to align them.



FIXED OFFSET BETWEEN THE FRAMES



The x- **axis** of Geomagic's pencil has to coincide to the z- **axis** of the KUKA's tool-tip. This **fixed rotational offset** must always be added to have a intuitive teleoperation.

WORKSPACE EXTENSION (1)

The first thing to underline is that master and slave do not have the same workspaces. A **clutching** mechanism is required to extend Geomagic limited workspace. This is done using the 3 buttons on the device.

BUTTON 1

- Fully releases the clutch between master and slave
- Slave **position** is modified
- Slave **orientation** is modified

BUTTON 2

- Partially releases the clutch between master and slave
- Slave position is not modified
- Slave **orientation** is modified

BUTTON 3

- Simulates a **virtual fixture**
- Motion allowed only along the ***z*-axis** of the slave's end effector (approaching dir.) while all the other components are filtered out.
- Slave orientation is not modified

WORKSPACE EXTENSION (2)

The software has to evaluate the **offset** between the current pose of slave's end effector and the current master pose *every time the user switches button.*

$$T_{slave} = \begin{pmatrix} R_s R_{off} & \mathbf{p}_s + \mathbf{p}_{off} \\ \mathbf{0}^T & 1 \end{pmatrix}$$

$$R_{off} = R_m(t_0)^T R_s(t_0)$$

$$\mathbf{p}_{off} = \mathbf{p}_s(t_0) - \mathbf{p}_m(t_0)$$

- In this way it is possible to command correctly and in a more intuitive way the slave through the haptic device. Slave position is not modified
- **If no button is pressed the slave will not move,** allowing the user to rearrange the master pose to be more comfortable for the task, or to achieve distant points inside the slave's workspace.

TELEOPERATION TASK

The aim of the project is use the *Geomagic Touch* **(master)** to simulate the teleoperation of a *KUKA LWR 4+* **(slave)**.

At each time-step, given the right **desired pose** $(\boldsymbol{p_d}\ \phi_d)^T$, the robot has to **converge** to it and a **force feedback** must be returned through the haptic device. Two main problems to be solved:

KUKA'S INVERSE KINEMATIC:

The system generates as input $\dot{\boldsymbol{r}}_d$ that must be turned into $\dot{\boldsymbol{q}}_d$ to be sent to the KUKA's low level controllers in order to generate the proper torques.

TELEOPERATION SCHEMES:

Three possible schemes have been developed in order to verify which one is more suited to a *needle insertion* task.

The system has been used to perform a **needle insertion** task, perforating a synthetic tissue modelled in the scene.

KUKA LWR 4+ INVERSE KINEMATICS (1)

Inverse kinematics of a redundant manipulator can be solved using different approaches.

STARTING FROM $\dot{\boldsymbol{r}} = J(\boldsymbol{q})\dot{\boldsymbol{q}}$

JACOBIAN-BASED METHODS → Gives a solution that minimizes a suitable norm, using $J(\boldsymbol{q})^{\#}$. For example: $\dot{\boldsymbol{q}} = J^{\#}\dot{\boldsymbol{r}}$ or $\dot{\boldsymbol{q}} = J^{T}(JJ^{T} + \mu^{2}I_{M})^{-1}\dot{\boldsymbol{r}}$.

NULL-SPACE METHODS → The simple solution of the pseudoinverse is enriched projecting in the null-space of J a velocity $\dot{\boldsymbol{q}}_0$, e.g. $\dot{\boldsymbol{q}} = J^{\#}\dot{\boldsymbol{r}} + (\boldsymbol{I} - J^{\#}\boldsymbol{J})\dot{\boldsymbol{q}}_0$.

TASK AUGMENTATION METHODS → An auxiliary task – or more than one – is added to the original one, imposing **priorities** between tasks, so $\dot{\boldsymbol{q}} = J^{\#}\dot{\boldsymbol{r}} + \mathrm{P}\mathbf{v}$ where $\mathbf{v}$ is calculated as $\mathbf{v} = (J_2\mathrm{P})^{\#}(\dot{\boldsymbol{r}}_2 - J_2J^{\#}\dot{\boldsymbol{r}}) + \left(I - (J_2\mathrm{P})^{\#}(J_2\mathrm{P})\right)\boldsymbol{w}$

In the system in analysis has been used a **null-space based method** to evaluate the right $\dot{\boldsymbol{q}}$ that we provide as inputs of the KUKA low-level controllers.

KUKA LWR 4+ INVERSE KINEMATICS (2)

In order to achieve smooth movements of the slave robot, it has been decided to discard the default VREP's IK group and to implement the following custom null-space-based IK.

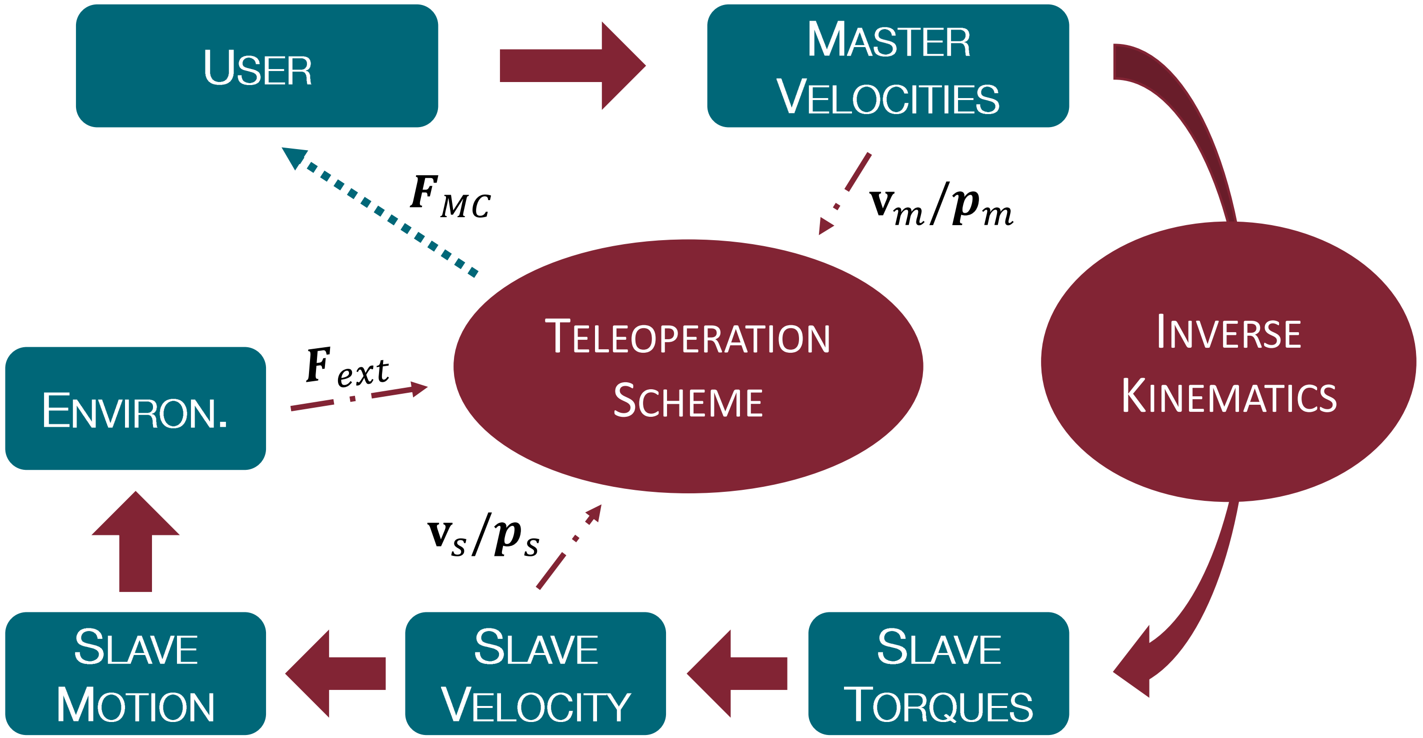
$$\dot{\boldsymbol{q}} = J^{\#}\boxed{\dot{\boldsymbol{r}}_d} + (\boldsymbol{I} - J^{\#}J)\boxed{\dot{\boldsymbol{q}}_0} \Longrightarrow \dot{\boldsymbol{q}}_0 = \boldsymbol{q}_{start} - \boldsymbol{q}$$

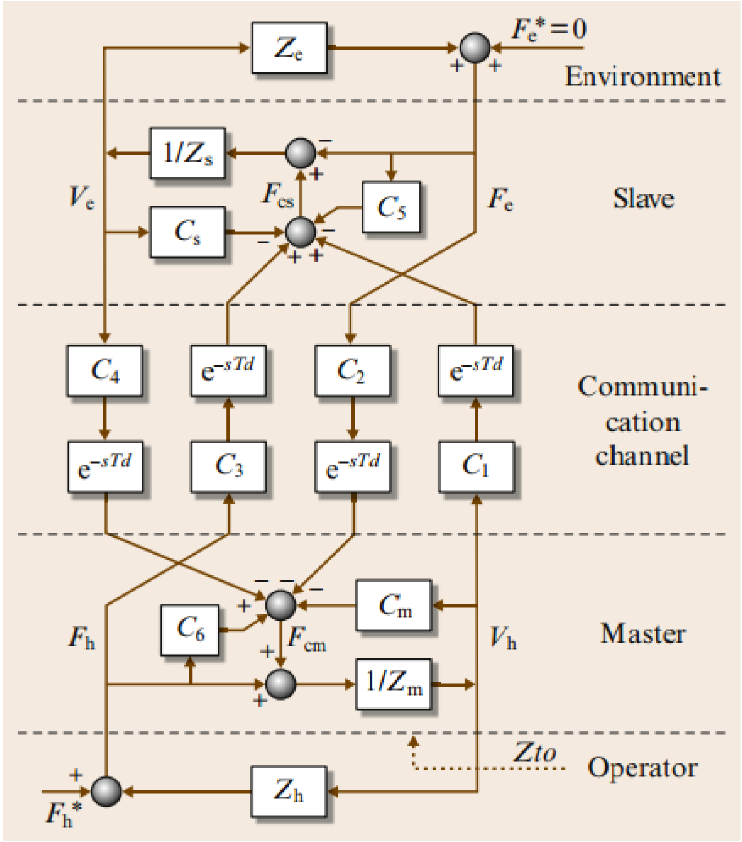
$$\dot{\boldsymbol{r}}_d = \begin{pmatrix} \mathbf{v}_d \\ \boldsymbol{\omega}_d \end{pmatrix} + K_p \mathbf{e}_{cartesian} = \begin{pmatrix} \mathbf{v}_d \\ \boldsymbol{\omega}_d \end{pmatrix} + K_p \begin{pmatrix} \boldsymbol{p}_d - \boldsymbol{p} \\ T_{xyz}(\phi)[\boldsymbol{\phi}_d - \boldsymbol{\phi}] \end{pmatrix}$$

Where $\mathbf{v}_d$ and $\boldsymbol{\omega}_d$ are the references, while the term $\mathbf{e}_{cartesian}$ is necessary to force the convergence of KUKA's end-effector to the desired pose.

TELEOPERATION SCHEMES (1)

Once that the system is able to generate desired pose references and that the slave is able to converge to them, a **force feedback** must be returned to the haptic device.





TELEOPERATION SCHEMES (2)

The system developed allow the user to choose between 3 teleoperation schemes:

POSITION – FORCE/POSITION

- Very popular among the schemes.
- It allows to *feel* the robot while moving **and** the external forces.

$$\boldsymbol{F}_{MC} = K_m \boldsymbol{F}_{sensor} - B_m(\mathbf{v}_m - \mathbf{v}_s)$$

POSITION - POSITION

- Simple and stable method: master and slave try to track each other.
- User *feels* only the **friction** and inertia in the slave robot.

$$\boldsymbol{F}_{MC} = -K_m(\boldsymbol{p}_m - \boldsymbol{p}_{md}) - B_m(\mathbf{v}_m - \mathbf{v}_{md})$$

POSITION - FORCE

- Gives a more clear sense of the environment.
- The user *feels* only the external forces that act on the slave robot.

$$\boldsymbol{F}_{MC} = K_m \boldsymbol{F}_{sensor}$$

TELEOPERATION: FILTERING VELOCITIES

CHAI3D synchronizes Geomagic's HL and VREP simulation loop, but velocity measures remain noisy: filtering is needed in order to generate smooth force feedbacks.

A **low pass filter** has been developed and used to filter the velocity measures used in the calculation of $\boldsymbol{F}_{MC}$.

WEIGHTED AVERAGE OF VELOCITY BUFFER

ACTUAL LOW-PASS FILTER

$$\mathbf{v}(t) = \mathbf{v}(t-1) + (\mathbf{v}(T) - \mathbf{v}(t-1)) * \left({}^{\Delta t}/_{(\Delta t + T)}\right)$$

SYNTHETIC TISSUE (1)

In order to perform the *needle penetration* it has been designed in VREP a model of a generic stratified biological tissue.

4 LAYERS STACKED TO COMPOSE THE TISSUE:

SKIN → FAT → MUSCLE → BONE

Analytical model used to design the tissue response to penetration. **Viscoelastic force** generated during insertion; force generated by:

- Springs
- Dampers

→

- Initially the layer **deforms** itself, due to its elasticity: the force exerted on the needle is described by a **spring model**.
- Reached the maximum deformation, perforation happens: from now on, the force is only due to **viscous friction**.

SYNTHETIC TISSUE (2)

Each layer has different physical parameters to generate a more realistic effect during the execution of the task.

SKIN

$$F = \begin{cases} k_s y & \text{upon contact} \\ b_s y v & \text{after puncture} \end{cases}$$

FAT

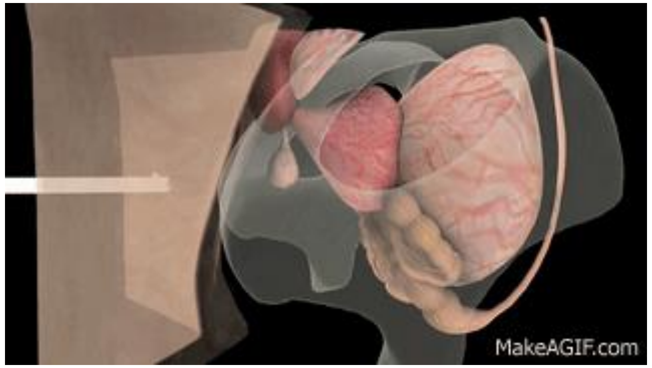
$$F = \begin{cases} k_f y + b_s y_s v & \text{upon contact} \\ (b_s y_s + b_f y)\, v & \text{after puncture} \end{cases}$$

MUSCLE

$$F = \begin{cases} k_m y + (b_s y_s + b_f y_f)\, v & \text{upon contact} \\ (b_s y_s + b_f y_f + b_m y)\, v & \text{after puncture} \end{cases}$$

BONE

$$F = k_b y + (b_s y_s + b_f y_f + b_m y_m)\, v \quad \text{upon contact}$$



Since VREP is not good in managing contacts between objects, it has been done an approximation to determine the fracture point: each layer will be perforated when a certain depth is reached – indicated through the parameter called *perforation depth*.

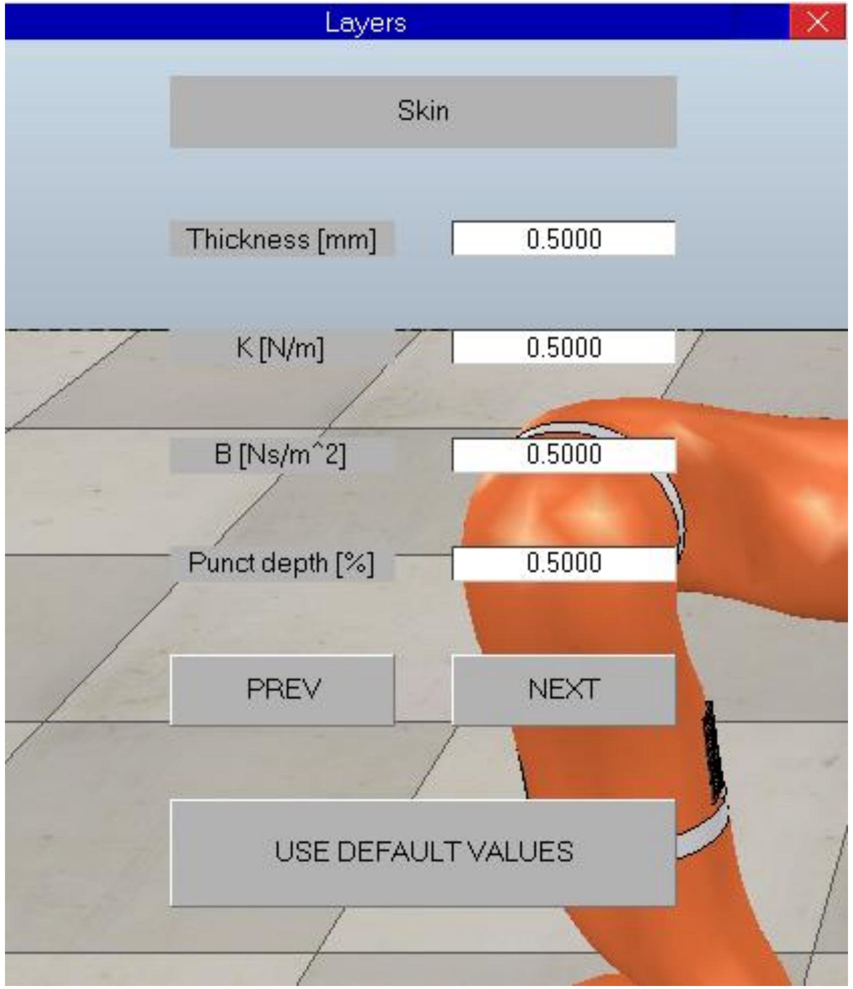
V-REP (HTTP://WWW.COPPELIAROBOTICS.COM/)

- Free, open-source, multi-platform robotics simulator
- Provides engines for dynamic/physics simulations
- Many robot models are available in the standard distribution
- It's functionalities can be extended using many programming languages (C/C++, Matlab) and programming approaches (remote clients, plugins, ROS nodes)

In our approach, we developed a C++ plugin in order to perform needle penetration simulation.

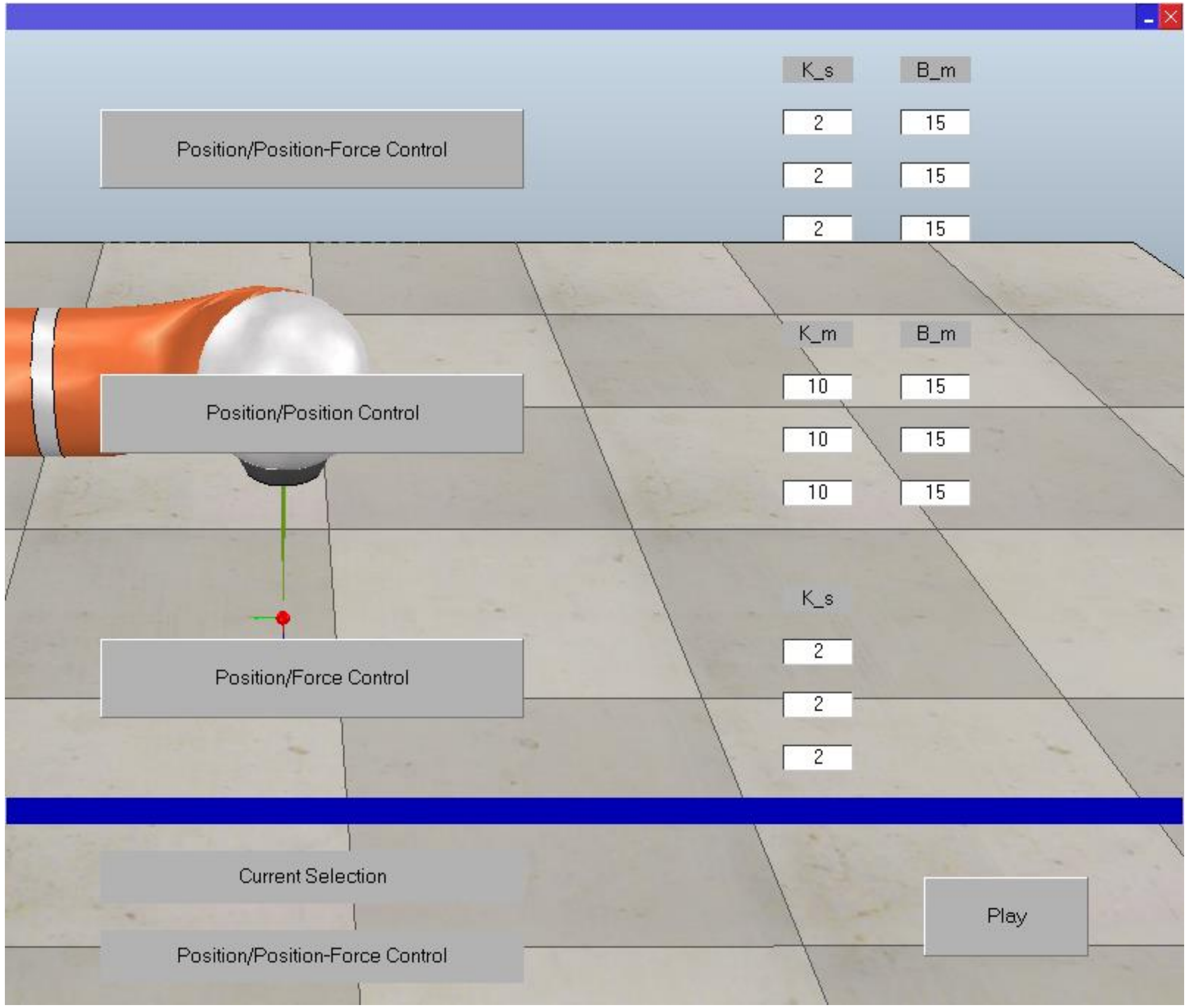
INTERFACES (LAYERS)

- The user is able to chose the parameters of the 4 layers
- Using the PREV/NEXT buttons the tab will switch between the layers
- If the user doesn't want to fill all the layers' parameters, he can use the default values we set on the code
- Once the choice is done, the user can close the window and switch to the following interface

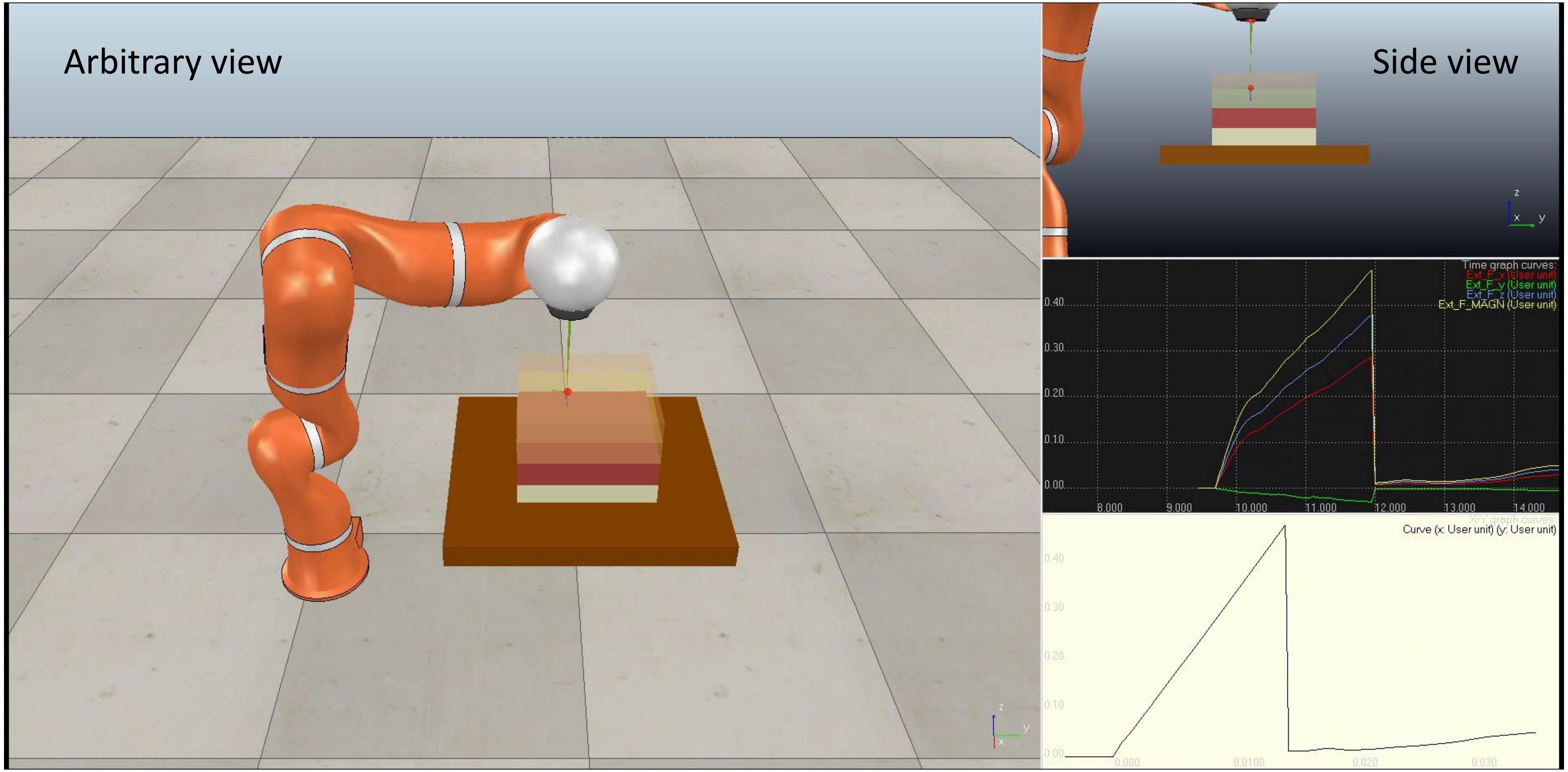


INTERFACES (CONTROLLER)

- Through this interface the user can select and set the parameters of a controller
- The current selection will be shown on the bottom section of the GUI
- Thanks to the "Play" button the simulation will start with the desired parameters



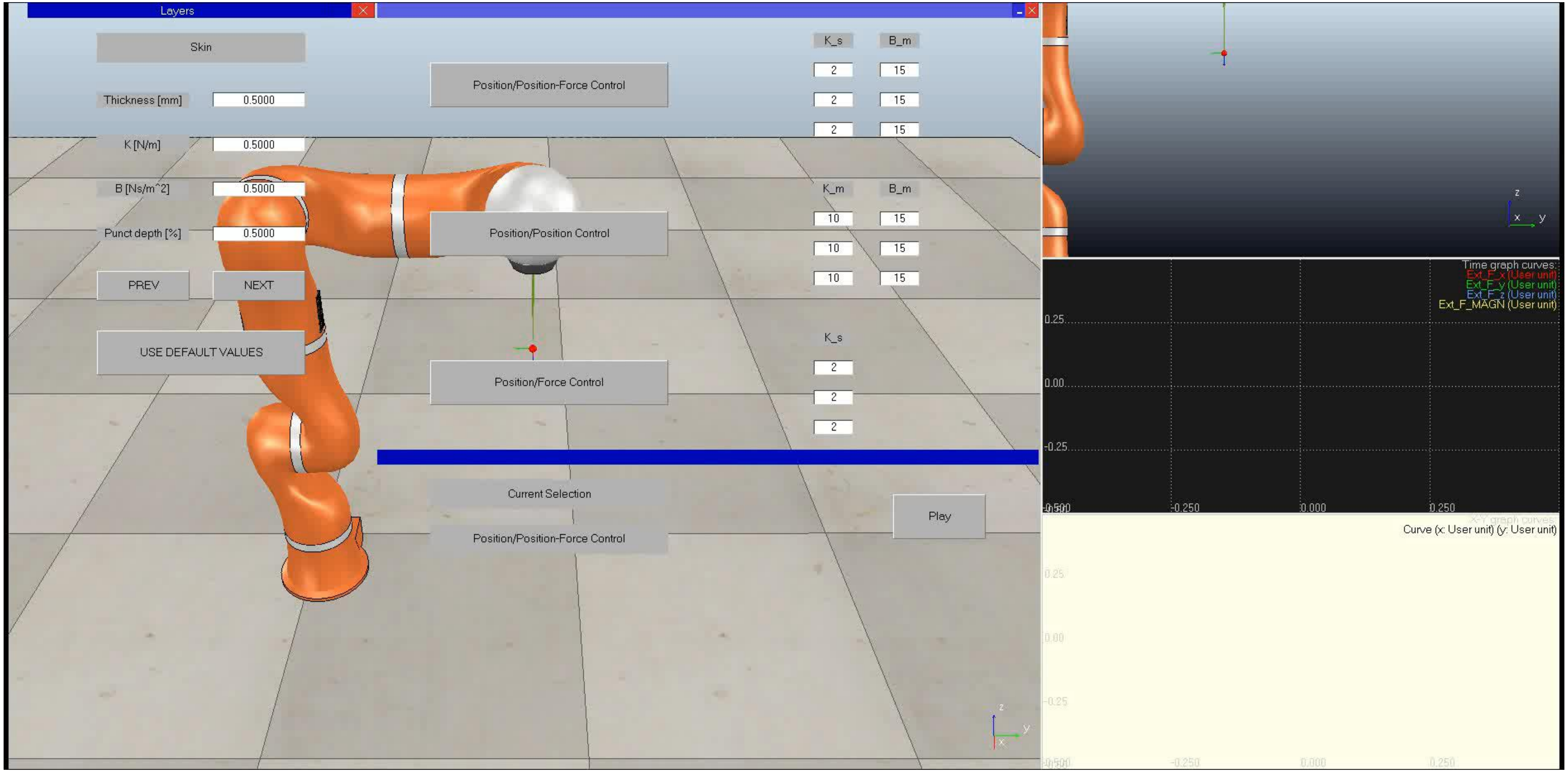
VIEWS



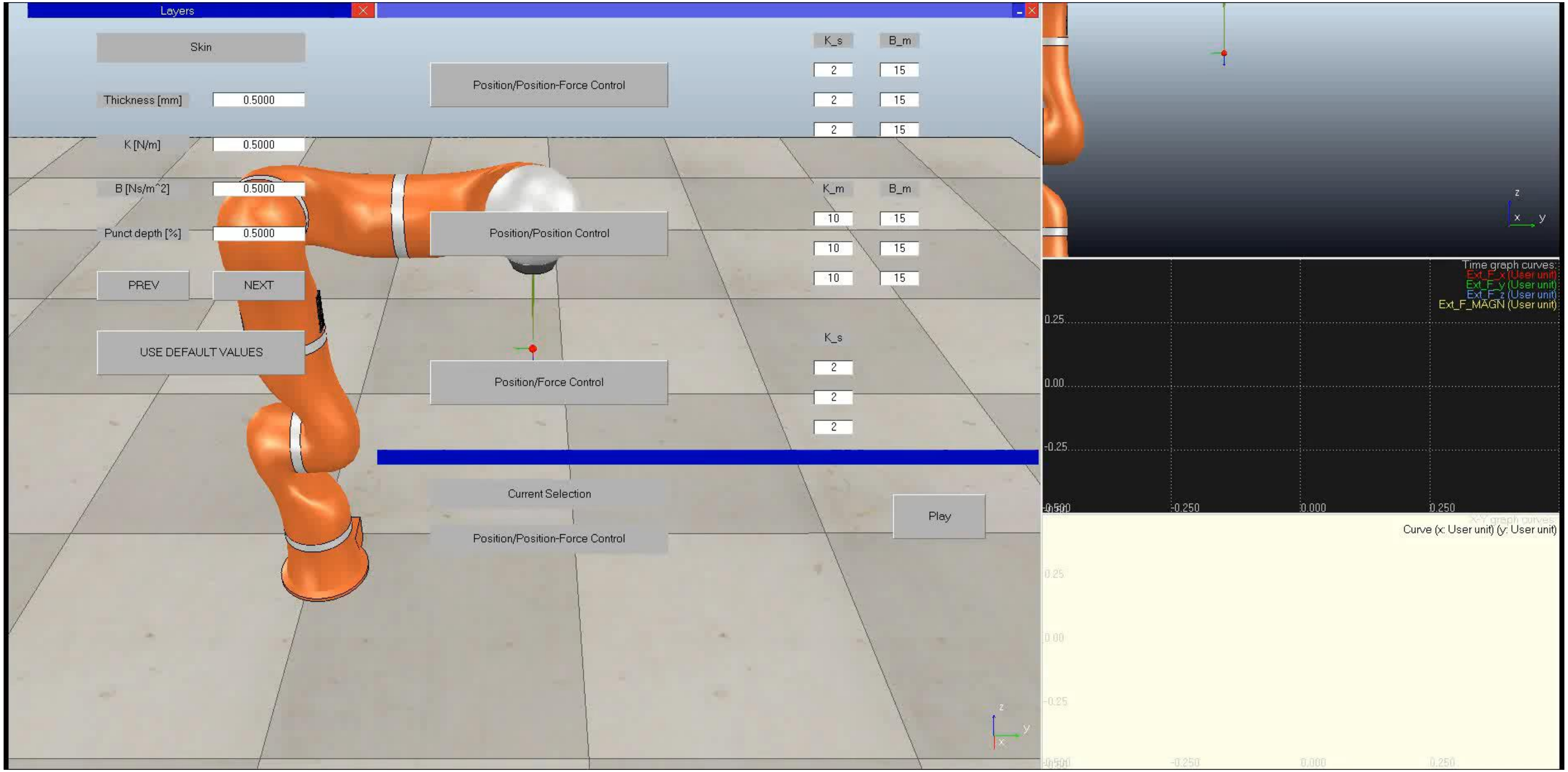
External forces graph

Depth/forces graph

Virtual Coupling

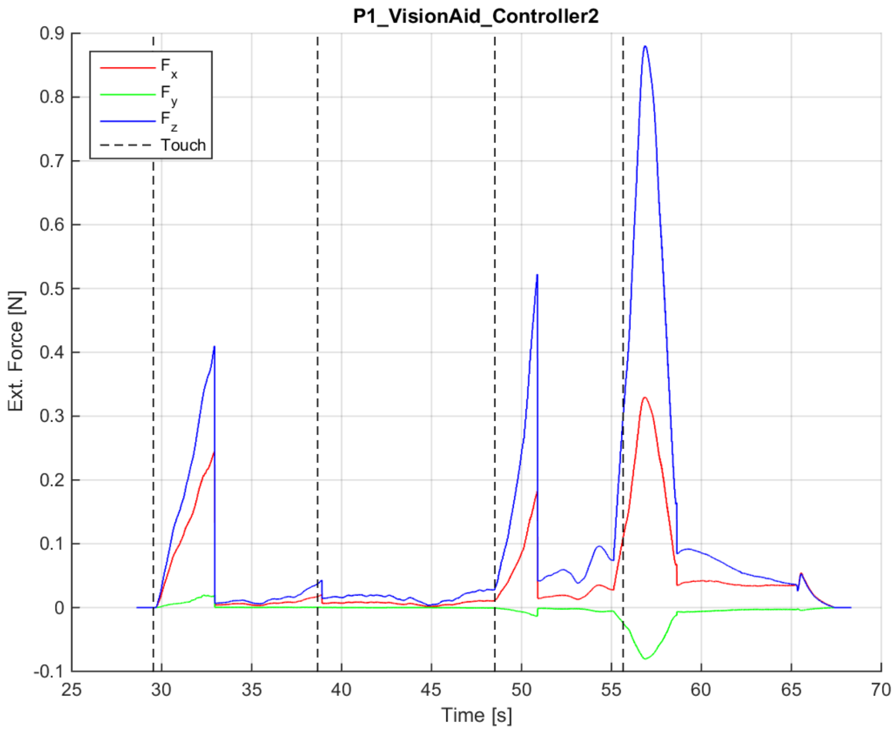


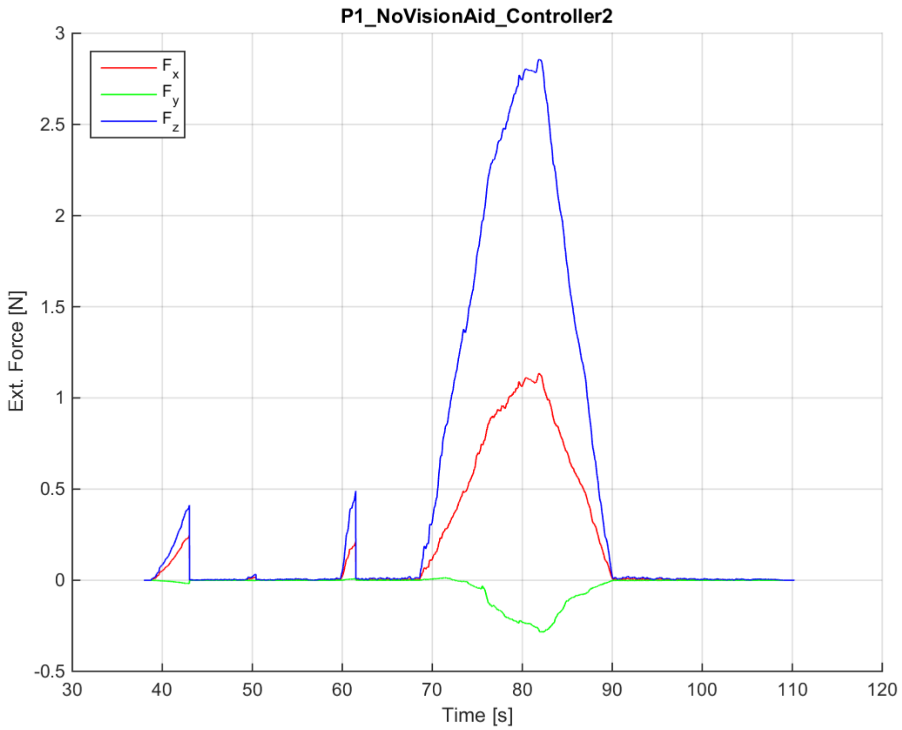
PENETRATION



Simulations

- **TASK:** complete penetration of the tissue and recognition the layers
- Comparison between **vision aided** and **haptic feedback only** simulations with different teleoperation schemes





Discussion and Future Works

- The aim of this project is to build a simulative framework in VREP in order to teleoperate a KUKA LWR 4+ robot using a Geomagic Touch as master robot implementing different teleoperation schemes
- The experiments underlined how some of the proposed teleoperation schemes are not suitable for such tasks
- VREP is not able to properly manage interactions between objects → different platform, e.g. *Unity*
- The device has a passive gimbal so cannot provide forces on its last 3 joints → a more professional haptic device allows users to perceive more realistic sensation
- This work can be transposed in real-word applications using a robot manipulator to accomplish this task

THANK YOU FOR YOUR ATTENTION!