POLYTECH
NICE-SOPHIA

Project: Computing FK and IK for a Robotic Arm

Project Objective: Write a program in C++ implementing the forward kinematic (FK) and inverse kinematic (IK) algorithms for a robotic arm.

The document is quite long as it contains lots of basis material, please read it carefully. The overall required work is not too complex if you follow the instructions.

In this project we shall use Blender to visualize the result. You are therefore invited to download this software before going further. To learn the basic, this youtube video is quite good.

1 - Background

1.1 3D Object in Space

A 3D object is defined by a list of points (vertices) and edges connecting theses vertices forming triangles.
When loaded in a 3D software tool, the objects are shown on the default position, without rotation or translation. It is well illustrated below, with a simple airplane object loaded in Blender
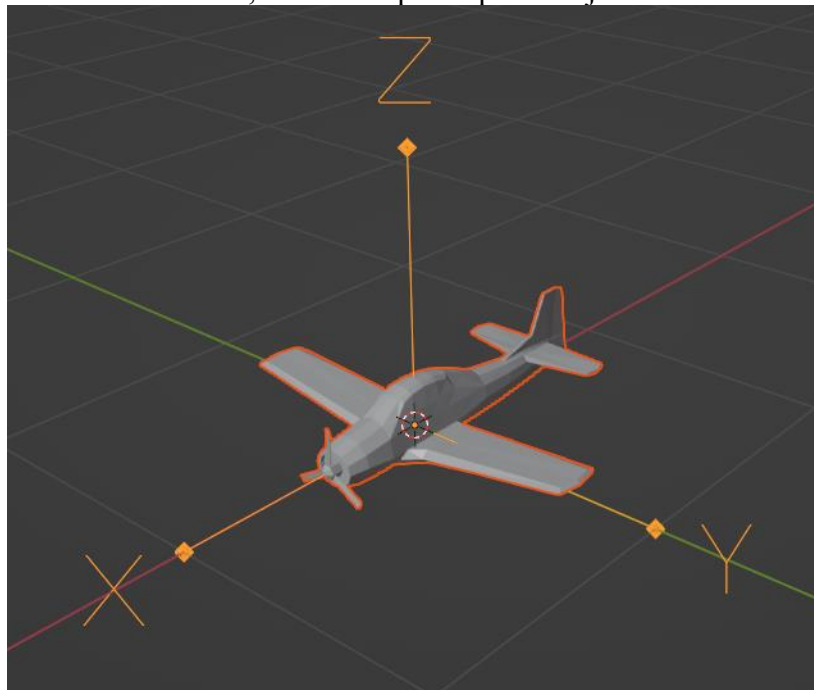

Figure 1. Default Object Position.

The object can be moved and rotated in the 3D space, so 6 values are needed to fully capture the position of the object vs the default position: 3 rotation values and 3 translation values.
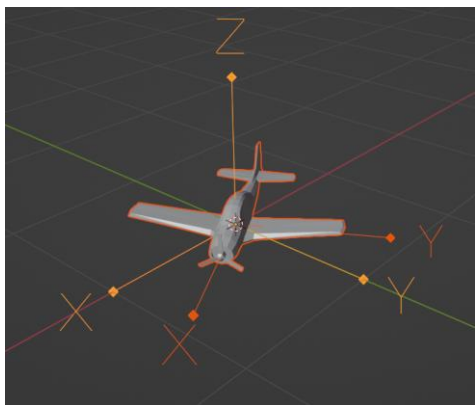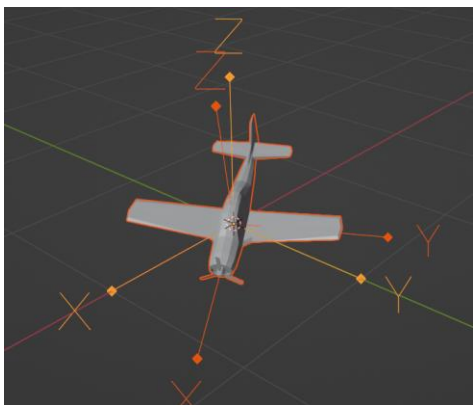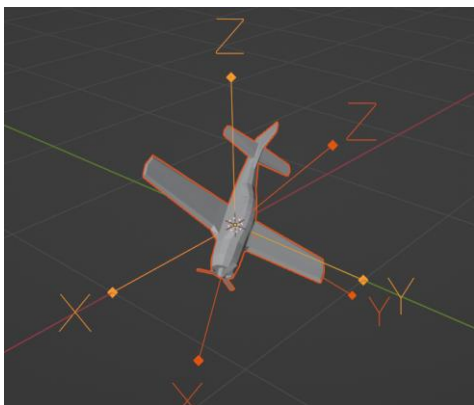
1.1.1 Rotation RPY

Rotations are defined on the *local frame* by 3 angles, done in the following order

- a yaw angle (α), rotation on the **z** axis, **x** and **y** becomes **x1** and **y1**
- a pitch angle (β), rotation on the **y1** axis, **x1** and **z** becomes **x2** and **z1**
- a roll angle (γ), rotation on the **x2** axis, **y1** and **z1** become **y2** and **z2**

Local frame means that the rotation axes are linked to the object as opposed to the global frame where the rotation axes are fixed.

Example: successive yaw, pitch and roll rotations using the local frame to express the rotation.

Yaw with $\alpha = 30°$	Pitch with $\beta = 20°$	Roll with $\gamma = -40°$
Yaw Rotation Matrix	Pitch Rotation Matrix	Roll Rotation Matrix
$R_z(\alpha) = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}$	$R_y(\beta) = \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}$	$R_x(\gamma) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{pmatrix}$

The overall rotation matrix can be expressed by multiplying these 3 matrices. As matrix multiplication is not commutative, we have shall only use that specific order in this document.
For reference, in Blender, rotation order can be selected, and the Blender order matching the one we have selected is called `XYZ Euler` as shown below. This specific order is also called `RPY`.
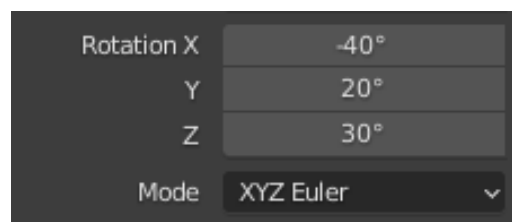

Figure 2. Blender Rotation Mode Selection.

Using the XYZ or RPY order, a vertex $V = \begin{pmatrix} v_x \\ v_y \\ v_z \end{pmatrix}$ belonging to the original object, is transformed in

vertex $V' = \begin{pmatrix} v'_x \\ v'_y \\ v'_z \end{pmatrix}$ using the following matrix transformation:

$$V' = R_z(\alpha) \cdot R_y(\beta) \cdot R_x(\gamma) \cdot V$$

The order of the matrix multiplications could be counter intuitive, but a rotation matrix is defined on the global reference axes, not on the local rotated axes.

1.1.2 Translation

Translation is defined by the 3 parameters t_x, t_y, t_z

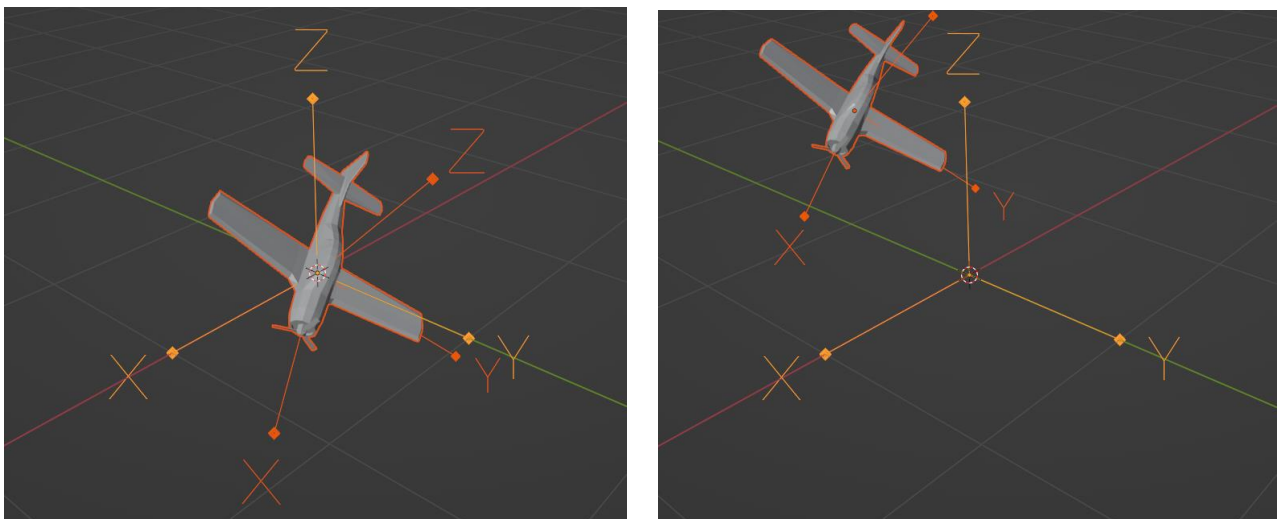Continuing with example, we show the images before and after translation

Figure 3. Object Translation Before After.
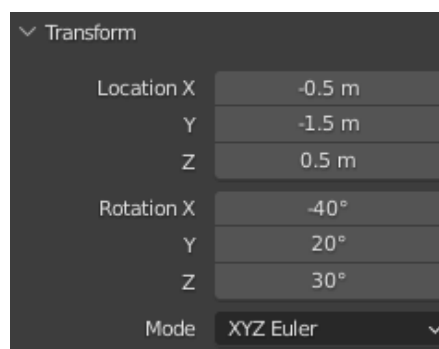
The 6 parameters are visible in Blender as:

Figure 4. Blender Translation and Rotation Parameters.

Translation cannot be expressed with a 3x3 matrix transform; we must use 4x4 matrices instead. The convention is that a 3D point, such as vertex V is represented by a 4-dimension vector:

$$V = \begin{pmatrix} v_x \\ v_y \\ v_z \\ 1 \end{pmatrix}$$

Rotation matrix are extended as shown in the example below:

$$R_x(\gamma) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\gamma) & -\sin(\gamma) & 0 \\ 0 & \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The translation matrix is defined by the following 4x4 matrix:

$$T = \begin{pmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

The final transformation is defined:

$$V' = T \cdot R_z(\alpha) \cdot R_y(\beta) \cdot R_x(\gamma) \cdot V$$

$$V' = M \cdot V$$

2 - Robotic Arm

In this lab, we shall use a model of the Gen3 robot from Kinova robotics, which has a comprehensive documentation and 3D models available for free.

- User Guide document: here
- Specification document: here
- Git repo here

Figure 5. Kinova Gen3 Robotic Arm.

The diagram below is the full picture of the robotic arm with the names of the all the links and the name of all the joints. We use the standard term "*link*" to refers to a rigid body that forms part of the robot arm's structure.

To limit complexity, (i) the base shall always be at the origin of the reference axes, (ii) the fingers shall not move and (iii) the "*effector*" link shall be used as the reference in the remaining of the document when considering the position of the robotic arm.
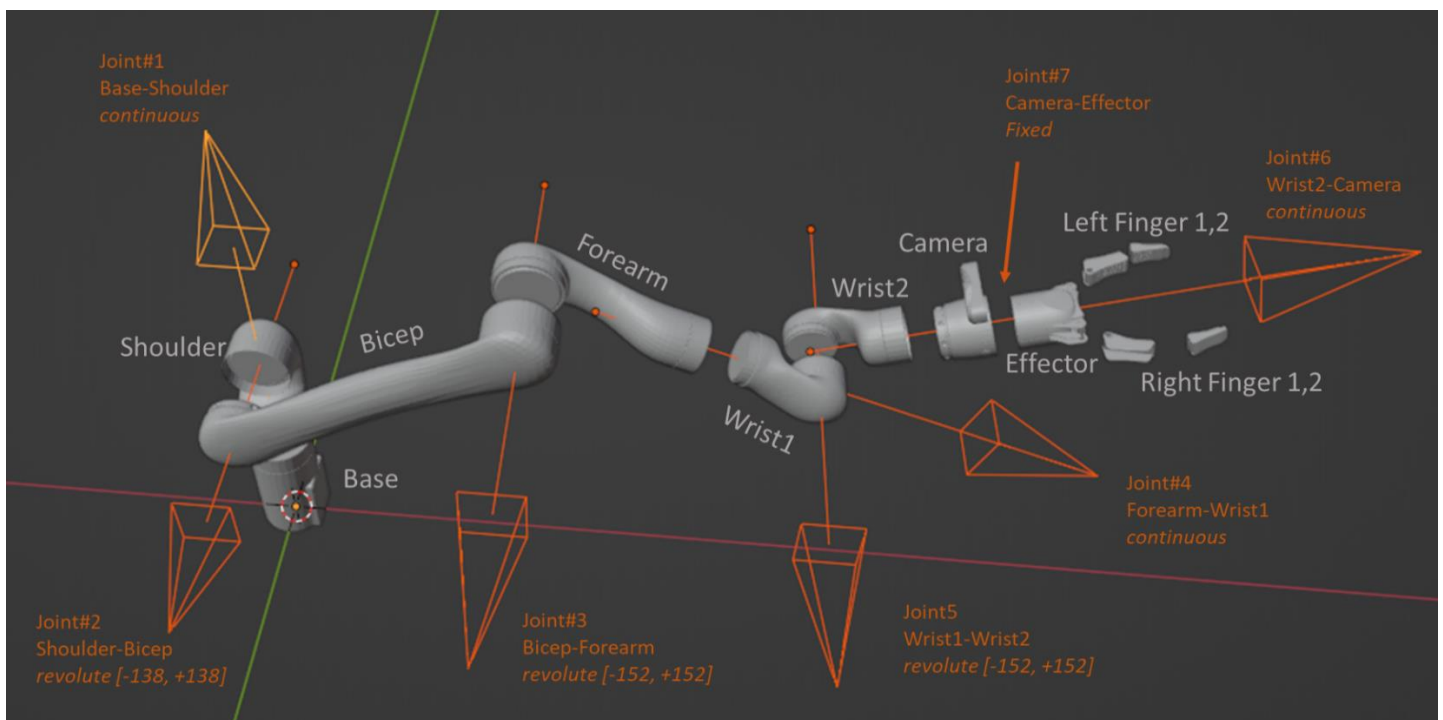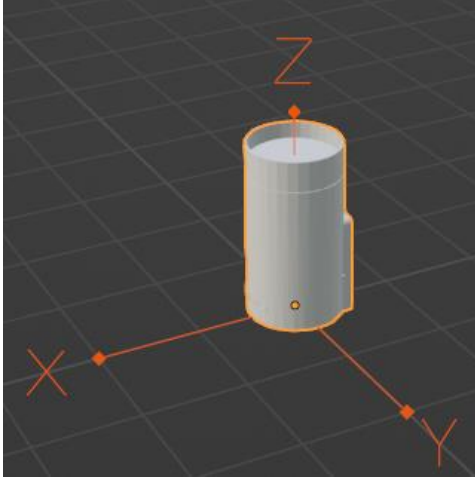

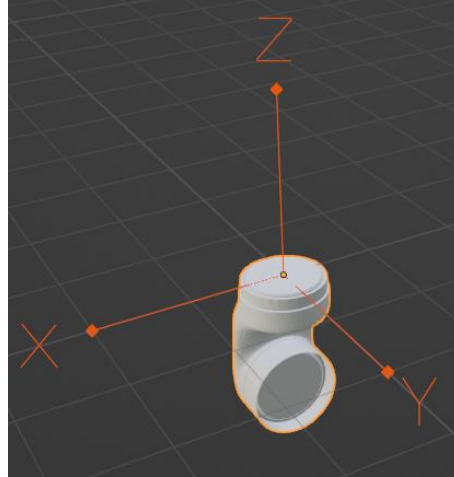Figure 6. Robotic Arm with Links and Joints.

2.1.1 Composing Robot Links

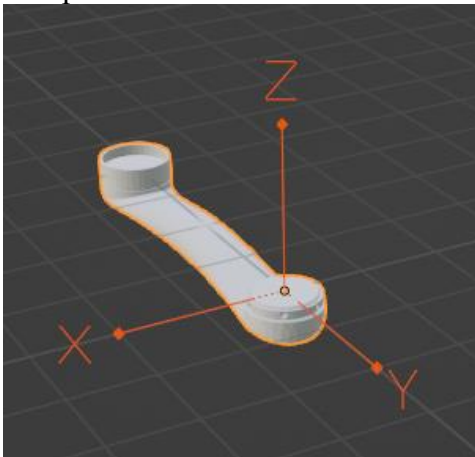Below is the first 4 links in default position:

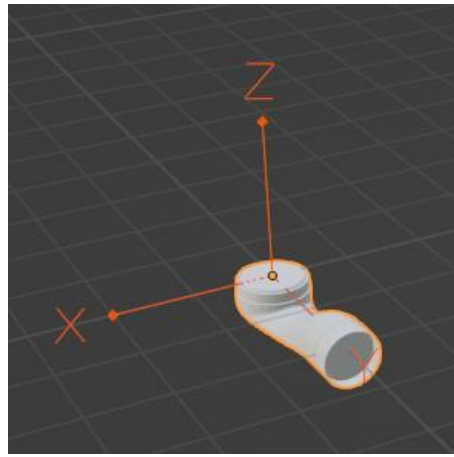Base

Shoulder

Bicep

Forearm

Figure 7. Links in Default Position.

To assemble the robot, the shoulder must be first placed onto the base.
The URDF file indicates the offset and rotation which must be applied to the shoulder so that it fits exactly on top of the base:

```
<joint name="Actuator1" type="continuous">
  <origin xyz="0 0 0.15643" rpy="-3.1416 0.0 0.0" />
  <parent link="Base_Link" />
  <child link="Shoulder_Link" />
  <axis xyz="0 0 1" />
  <limit effort="39" velocity="0.8727" />
</joint>
```

The statement `<origin...>` describes the rotation and translation which must be applied to the shoulder.

More details on URDF file format can be found here.

Shoulder before and after the rotation given by: `rpy="1.5708 0.0 0.0"`, this rotation is a 180° roll. Note how the local axis have changed as they are attached to the shoulder
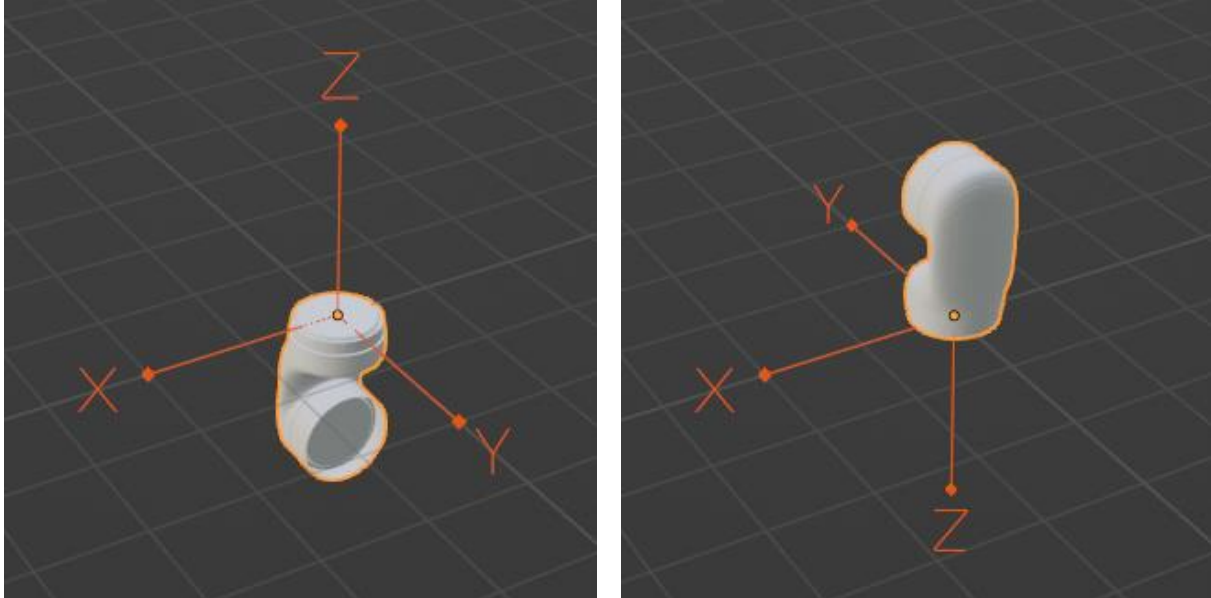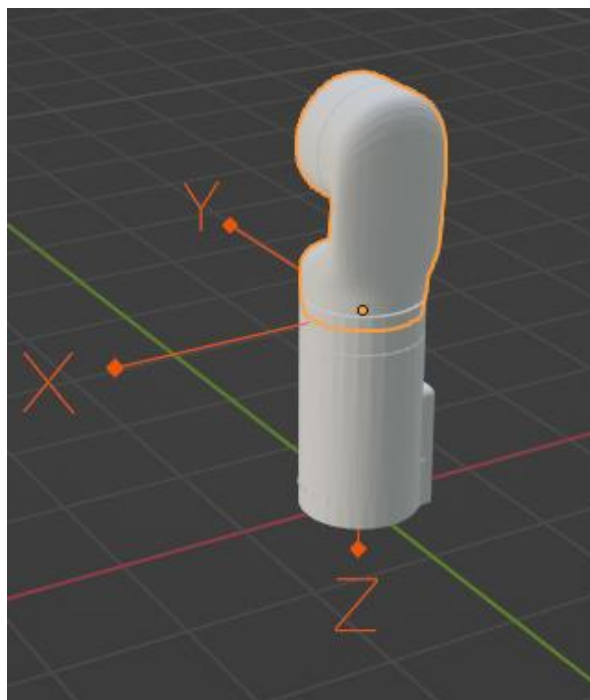

After translation given by `xyz="0 0 0.15643"`

Figure 8. Composition of Links.

Using the 4x4 matrices described above and the UDRF description for joint 1, we can easily compute 2 matrices: R_1, and T_1. The overall transformation for the shoulder link is then given by:

$$Q_1 = Q_0 \cdot T_1 \cdot R_1$$

Q_0 is the transformation matrix of the base. We will assume that the base is located, as shown above, on the origin of the global space, so Q_0 is the identity matrix.

To add the bicep, we refer to the following section of the URDF:

```
<joint name="Actuator2" type="revolute">
  <origin xyz="0 0.005375 -0.12838" rpy="1.5708 0.0 0.0" />
  <parent link="Shoulder_Link" />
  <child link="Bicep_Link" />
  <axis xyz="0 0 1" />
  <limit lower="-2.41" upper="2.41" effort="39" velocity="0.8727" />
</joint>
```

From the above URDF, we can build two 4x4 transform matrices: R_2 and T_2

All the transforms in the URDF are related to the local reference frame of the parent.
So we have to proceed with 2 steps:
1) Apply R_2 then T_2 transforms to the bicep object.
2) Apply rotation and translation given by R_1 and T_1,

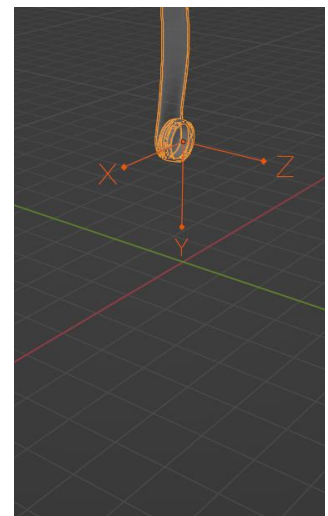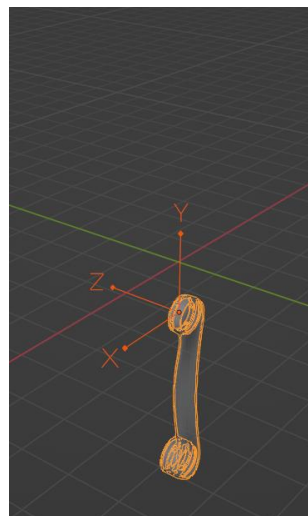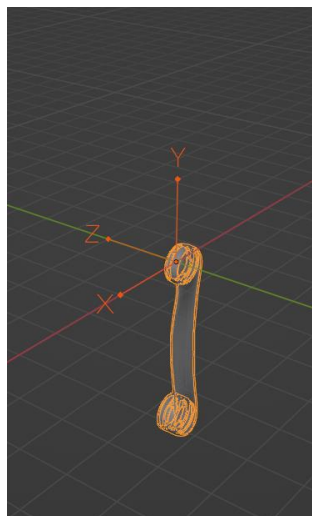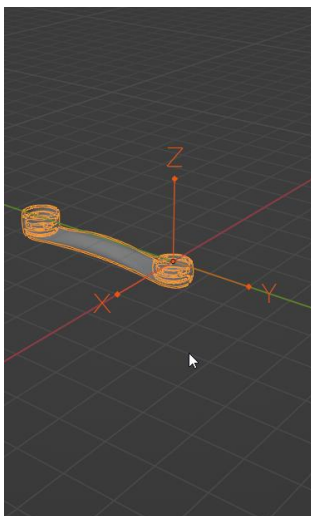| Default Position	After rotation by R_2	After $T_2 \cdot R_2$	After Q_1

Figure 9. Step by Step Composition of Links.

Considering the global origin, it can be shown, that the bicep transform is given by:

$$Q_2 = Q_1 \cdot T_2 \cdot R_2$$

The process can be continued with the forearm:

```
<joint name="Actuator3" type="revolute">
  <origin xyz="0 -0.41 0" rpy="3.1416 0 0" />
  <parent link="Bicep_Link" />
  <child link="ForeArm_Link" />
  <axis xyz="0 0 1" />
  <limit lower="-2.66" upper="2.66" effort="39" velocity="0.8727" />
</joint>
```
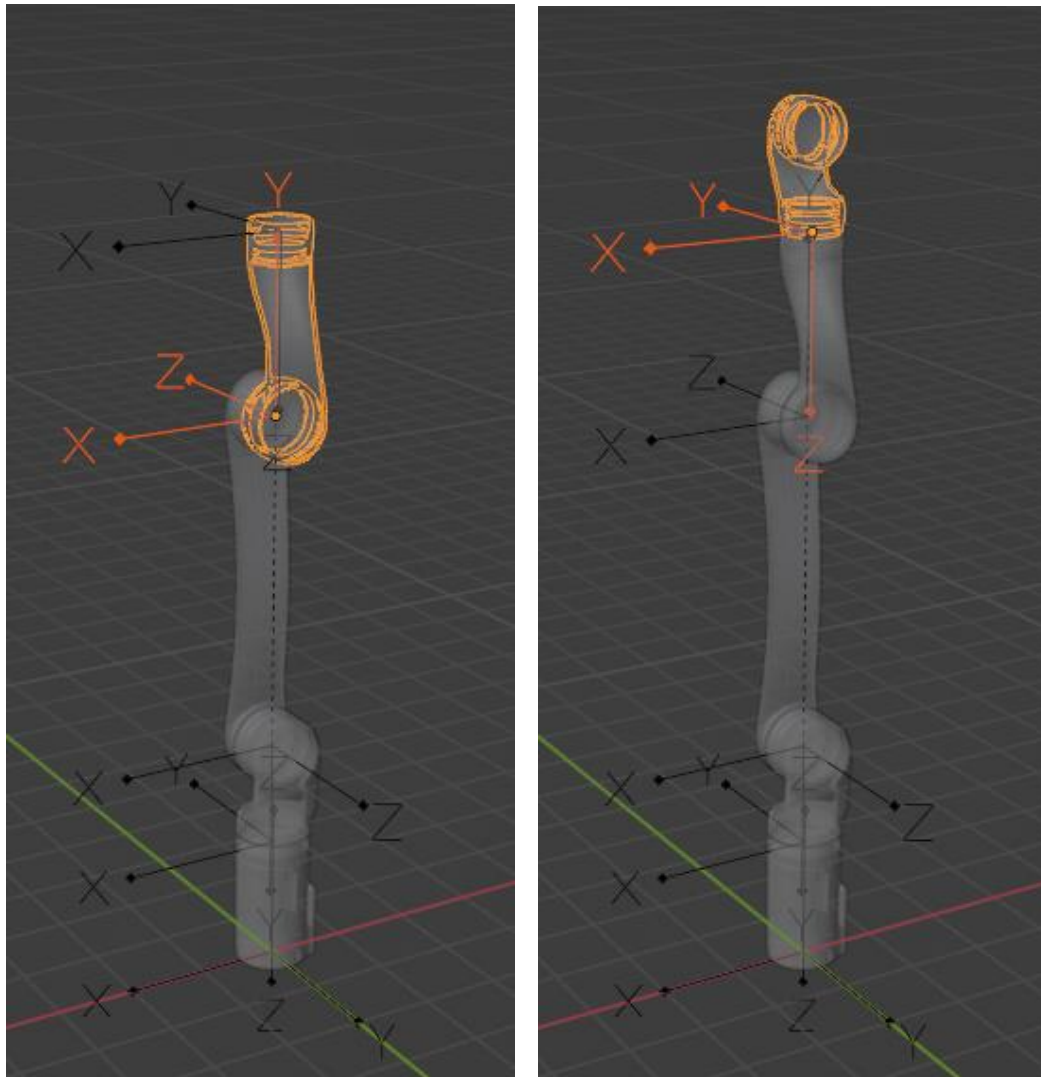

Figure 10. 4th Link Composition.

Given the URDF extract shown above for the 3rd joint, we build the rotation and transform matrices: R_3, and T_3. The global transform matrix for the forearm is given by:

$$Q_3 = Q_2 \cdot T_3 \cdot R_3$$

The transform matrix for the ith link is computed equally, using the recursive rule:

$$Q_i = Q_{i-1} \cdot T_i \cdot R_i$$

2.1.2 Rotation of the Robot's Joints

The axis of rotation is given by the URDF of the joint:

```
<joint name="Actuator2" type="revolute">
  <origin xyz="0 0.005375 -0.12838" rpy="1.5708 0.0 0.0" />
  <parent link="Shoulder_Link" />
  <child link="Bicep_Link" />
  <axis xyz="0 0 1" />
  <limit lower="-2.41" upper="2.41" effort="39" velocity="0.8727" />
</joint>
```
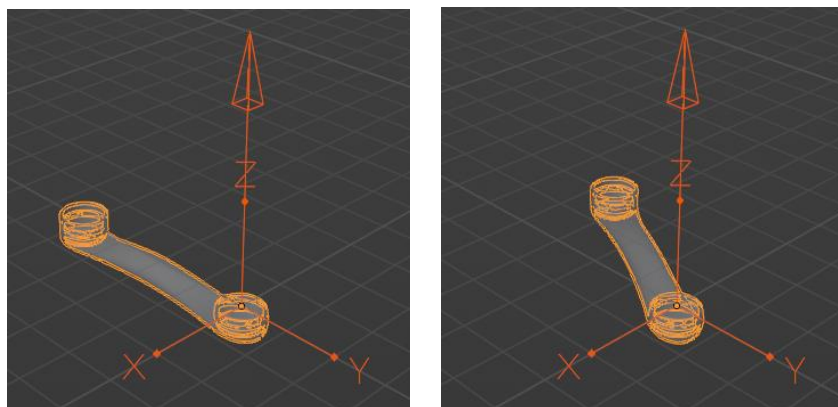
Rotation of the bicep shown in its default position (before and after) along the specified axis: it's yaw of -30°.

Figure 11. Link Rotation.

The rotation matrix of the ith joint by an angle θ_i is expressed by $A_i(\theta_i)$.

It can be shown that transformation of the ith link, is given by the following recursive definition:

With:

$$Q_i(\theta_1, \theta_2, \dots, \theta_i) = Q_{i-1}(\theta_1, \dots, \theta_{i-1}) \cdot T_i \cdot R_i \cdot A_i(\theta_i)$$

$$Q_1(\theta_1) = T_1 \cdot R_1 \cdot A_1(\theta_1)$$

Main Transform Formula

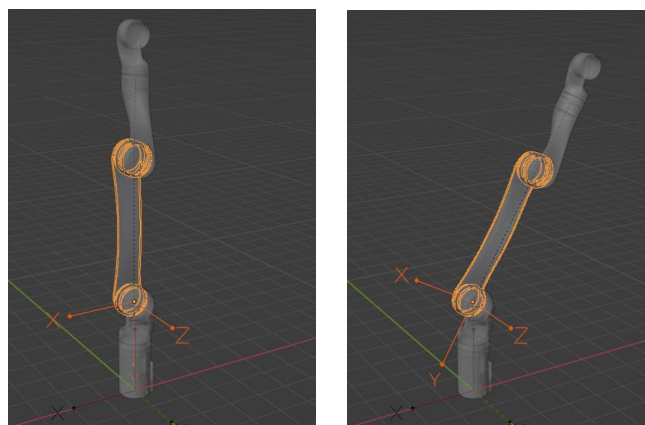Overall robot before and after a rotation of $\theta_2 = -30°$

Figure 12. Link Composition with Joint Angle.

3 - Forward Kinematics (FK)

3.1 Problem Statement

Given a list of 6 joint angles ($\theta_1, \theta_2, \ldots \theta_6$) find the 3D position of all the links composing the robot. This is a simple problem which can be solved by applying iteratively the main transformation formula of the previous section.

3.2 What must be done.

1) Install the package, compile, and cross-check that your installation is correct, see the appendix on the how to.

2) In the method Robot::forward_kinematic(…) add your version of the forward kinematic. The GLM package shall be used for all vector and matrix operations, check the appendix section to learn more on GLM.

3) Validate your code against my output shown below. See next section for some hints on how to use existing methods to achieve the expected result.

```
shell> ./robot_kinematic.exe  --angles -70,-50,90,0,-50,-90
#############################################################################
##            Forward and Inverse Kinematic (Release version 1.0)        ##
##     Compiled on Sat Aug 31 18:31:52 2024 from source ID cb91eea48317+3     ##
#############################################################################
[INFO]  Parsing config file config.toml
multiple lines removed
[INFO]  +++++++++++++++++++++++++++++++++++++++++
[INFO]  Information for robot 'Kinova Gen3 6DF with vision'
[INFO]  Number of links     12
[INFO]  Number of joints    11
[INFO]  Degrees of freedom  6
[INFO]  Root link           L00.Base
[INFO]  Target link         L07.Effector
[INFO]  +++++++++++++++++++++++++++++++++++++++++
[INFO]  Compute forward kinematic with angles -70,-50,90,0,-50,-90
[INFO]  Target position (x, y, z) = (-0.23507285, -0.64191204, 0.30754)
[INFO]  Target rotation (r, p, y) = (0, 90, -109.99959)
Target Transform = {
  {        0,     0.9397,    -0.34201,    -0.23507}
  {        0,    -0.34201,    -0.9397,     -0.64191}
  {       -1,          0,           0,      0.30754}
  {        0,          0,           0,            1}
}
[INFO]  --------------------------------
[INFO]  Generate blender script to file my_script.py
[INFO]  Script file generated with 2 poses
```

3.3 Robot Link and Joint Methods.

The sample code already builds a robot object from a config file. TOML format has been chosen to describe the robot links and joints instead of the XML format as TOML is much simpler than XML for human to read and for a computer program to parse.

The diagram below illustrates the key method of the Joint and Link classes which form a Robot class. Less than 50 lines of codes are needed in the method Robot::forward_kinematic() to have this work.
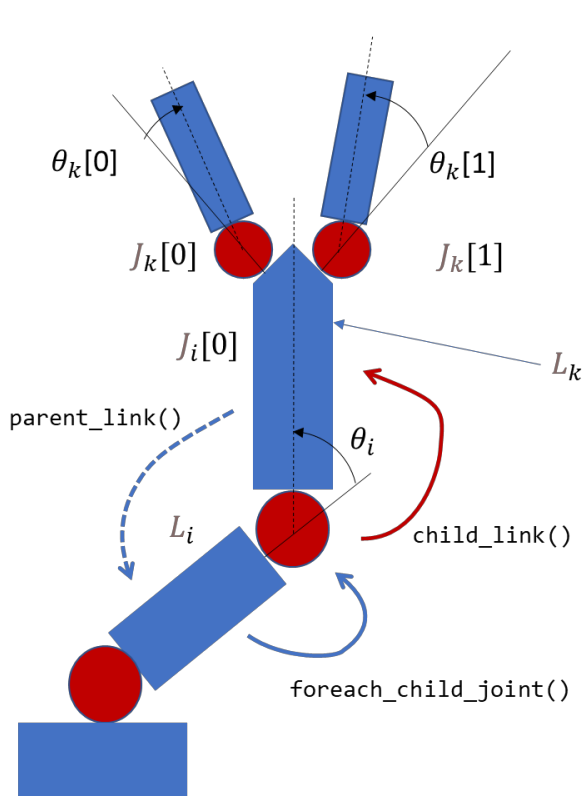
Global Transform for link L_k

$$Q_k = \overbrace{Q_i \cdot T_i \cdot R_i \cdot A_i(\theta_i)}$$

Local Transform

```cpp
class Joint {
 private:
  Link* p_child_link_;
  Link* p_parent_link_;
 public:
  Link *child_link() const;
  void set_angle(float);
  glm::mat4 get_local_transform() const;
  ...
};
```

```cpp
class Link {
 private:
  std::vector<Joint*> pjoints_;
  Link* p_parent_link_;
 public:
  void foreach_child_joint(std::function<void(Joint*)> callback);
  glm::mat4 get_transform() const;
  void set_transform(const glm::mat4&);
  Link *parent_link() const;
};
```

The list of angles must be applied to the non-fixed joints, based on the order found in the file. Traversing the robot links and joints from the root using the methods listed above guarantee this order.

```toml
[[joints]]                -70,-50,90,0,-50,-90
name = 'J00'
type = 'continuous'
...
[[joints]]
name = 'J01'
type = 'revolute'
...
[[joints]]
name = 'J02'
type = 'revolute'
...
```
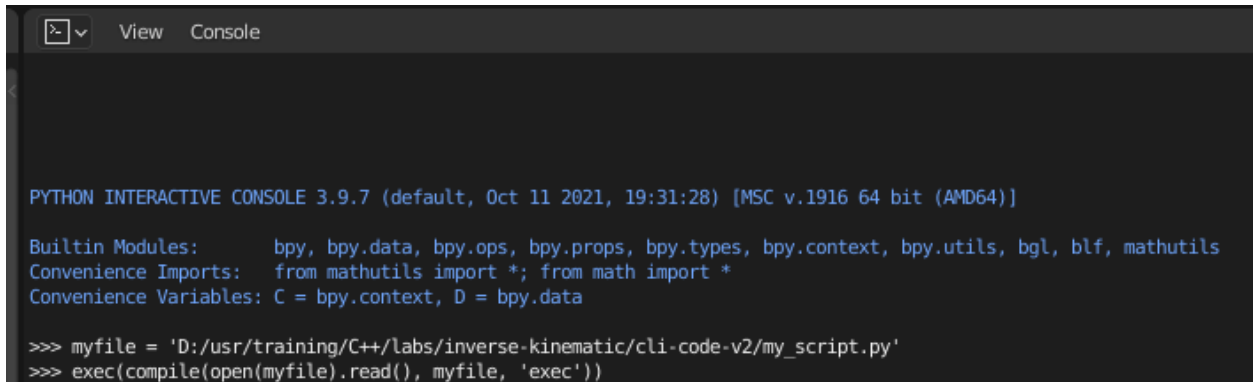
Figure 13. Relationship between Angles and Joints.

3.4 Visualization in Blender

You may have noted that the code generates a file called `my_script.py` which can be run in Blender python console after loading the blender project. The instructions to run the generated script are given in the script it self.
The trace is shown below:

Figure 14. Blender Python Console.

After execution of the script, you will be able to see the robot in a position matching the angles that you have provided.
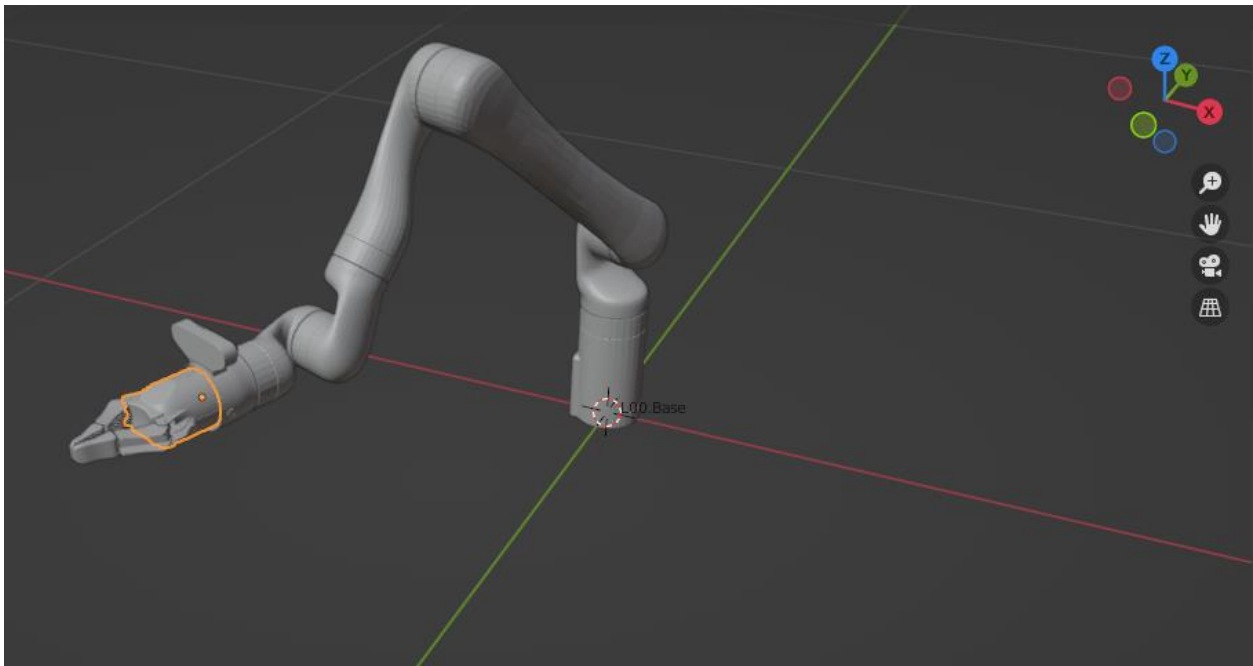

Figure 15. Robot Position for the Given Angles -70,-50,90,0,-50,-90.

4 - Inverse Kinematics (IK)

4.1 Problem Statement

Given a position T (target position) of the end effector in 3D space, i.e. the matrix Q_{eff} , find the angle values of the 6 joints $(\theta_1, \theta_2, \dots \theta_6)$, such that the computed position matches the target position.

IK is well-known problem which has extensively studied, many algorithms have been proposed. In this lab, we will be using the Cyclic Coordinate Descent (CCD) algorithm [more information].

CCD is an iterative algorithm, so we define T_i, the pose of the robot after the ith iteration, the pose is determined by the angles $(\theta_{1,i}, \theta_{2,i}, \dots \theta_{6,i})$, we also define $\Delta_i = \|T_i, T\|$, a distance metrics between the current pose and the target pose.

,
In the simplest variant, CCD iterates as many times as needed, by selected randomly one of the 6 angles, say the kth and searching for new value of the angle, $\theta_{k,i+1}$, such as $\Delta_{i+1} < \Delta_i$, i.e. the current pose is closer to the target pose. It is possible that a change on the kth angle does not improve the solution.

A nice interactive demo can be found https://rodolphe-vaillant.fr/entry/114/cyclic-coordonate-descent-inverse-kynematic-ccd-ik

The user can move the target (T) represented by the blue cube, and the IK algorithm immediately computes the angles for the different links.
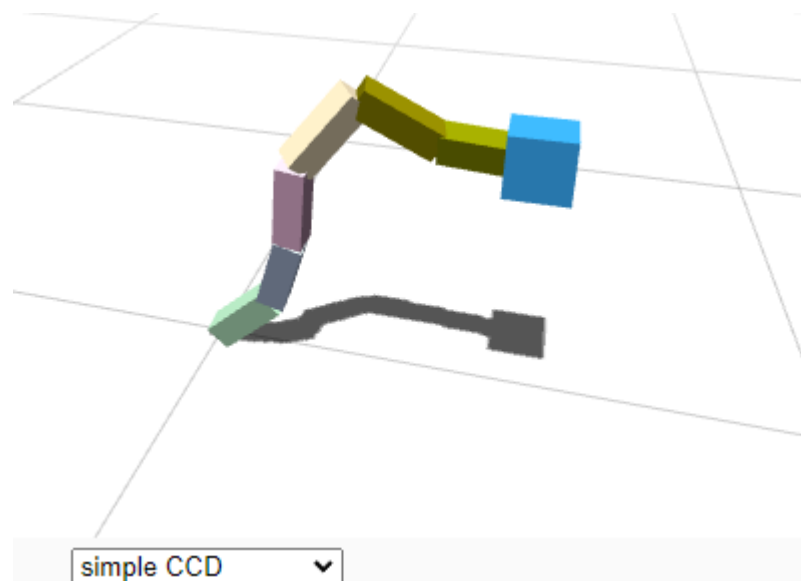

Figure 16. Inverse Kinematic of a Simple Robot.

4.2 Execution Trace

To help you debug your implementation, you will find an execution trace below.
The first part of the trace is identical to the trace shown in the forward kinematic section.

```
shell> ./robot_kinematic.exe --angles -70,-50,90,0,-50,-90 --xyz 0.302,-0.594,0.486 --rpy 0,90,-90
###############################################################################
##           Forward and Inverse Kinematic (Release version 1.0)          ##
##      Compiled on Sat Aug 31 18:31:52 2025 from source ID cb91eea48317+3     ##
###############################################################################
[INFO]  Parsing config file config.toml
multiple lines removed same as forward kinematic
[INFO]  --------------------------------
[INFO]  --   Start Inverse Kinematic   --
[INFO]  --------------------------------
[INFO]  Using seed 1294732963
[INFO]  Target position is (0.302,-0.594,0.486)
[INFO]  Target rotation is (0,90,-90)
[INFO]  CCD iteration   10, cost is 0.32202473
[INFO]  CCD iteration   20, cost is 0.23252723
[INFO]  CCD iteration   30, cost is 0.17262703
[INFO]  CCD iteration   40, cost is 0.13303311
[INFO]  CCD iteration   50, cost is 0.100779735
[INFO]  CCD iteration   60, cost is 0.078131855
[INFO]  CCD iteration   70, cost is 0.06396078
[INFO]  CCD iteration   80, cost is 0.051985282
[INFO]  Final distance is 0.049736887
[INFO]  Joint angles are (-123.5,-33.5828,82.6932,-50.6,-37.5696,-46.2)
[INFO]  --------------------------------
[INFO]  --    Write Blender Script     --
[INFO]  --------------------------------
[INFO]  Generate blender script to file my_script.py
[INFO]  Script file generated with 3 poses
```

Important points:
- CCD algorithm relies on random numbers to select the next joint, every time the program is run, the results could be different. If you need to repeat the exact same results, you can use the seed option, as shown below. The trace prints the seed value, which can then be copied and pasted as the integer value
  ```
  --seed integer      Force the seed for the random number generator
  ```
- The number of iterations is also key for the CCD algorithm, you can control this number with the iteration option:
  ```
  --iterations integer    Number of iterations for the CCD IK computation
  ```
- If you need to try several variants, use the method option which can be used to enable/disable part of your code (if needed).
  ```
  --method string      Extra option to enable variants in CCD IK computation
  ```

4.3 Distance Metrics

It is critical that you define a correct distance metric.
If you use a simple distance between the current pose and the target pose, you will obtain a solution shown on the left-side screen capture: it's close but the robot effector is not aligned with the target effector position shown in orange. With a proper distance metrics, used on the right-side screen capture, the computed effector position and the target position are almost identical.
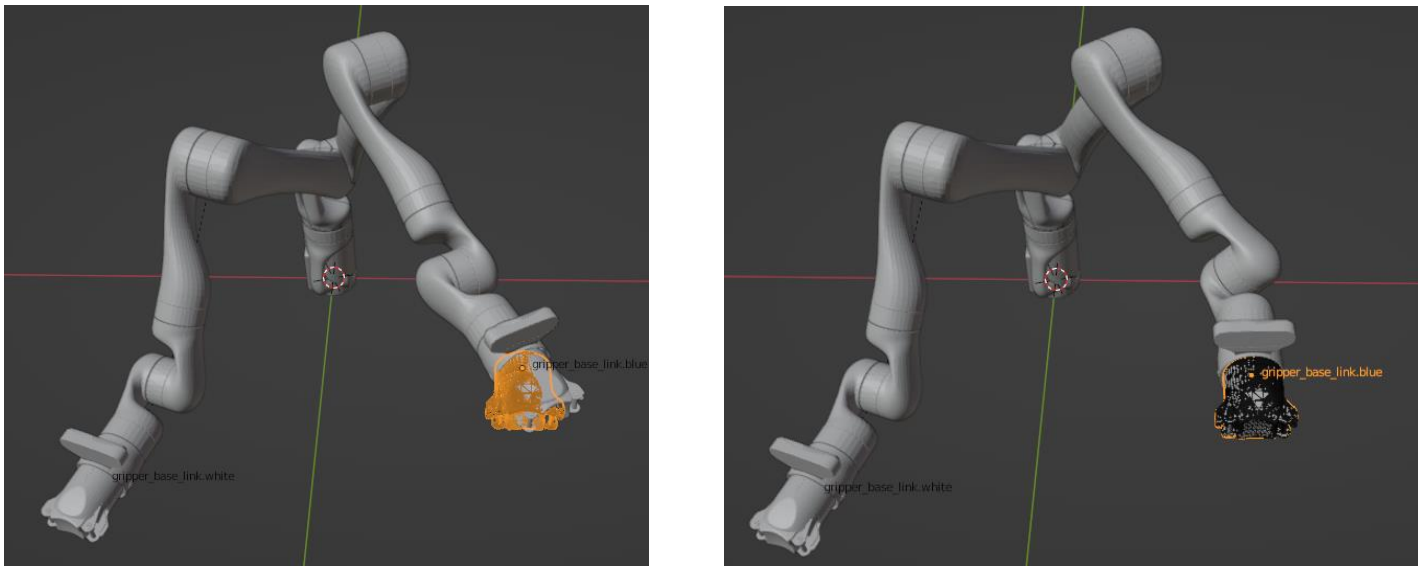

Figure 17. Incorrect and Correct Solution of the IK Problem.

Hint: don't re-invent the wheel and have a close look at the existing code, an interesting class is already there.

4.4 Collision Detection (Optional)

Make sure that the solution is realistic. In the picture below, part of the bicep and the forearm are below the table level, this is not an acceptable solution.
You will propose a way to avoid such scenario.
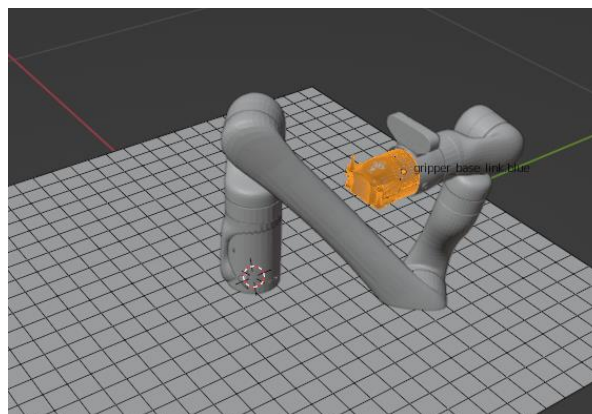
Figure 18. Incorrect Solution of the IK Problem.

4.5 Local Minimum (Optional)

The CCD algorithm belongs to the class of "greedy algorithm" and therefore can be stuck in a local minima. On the left side, it is impossible for CCD to converge toward the solution. A second try with a different random sequence, shown on the right picture, converges toward the solution.
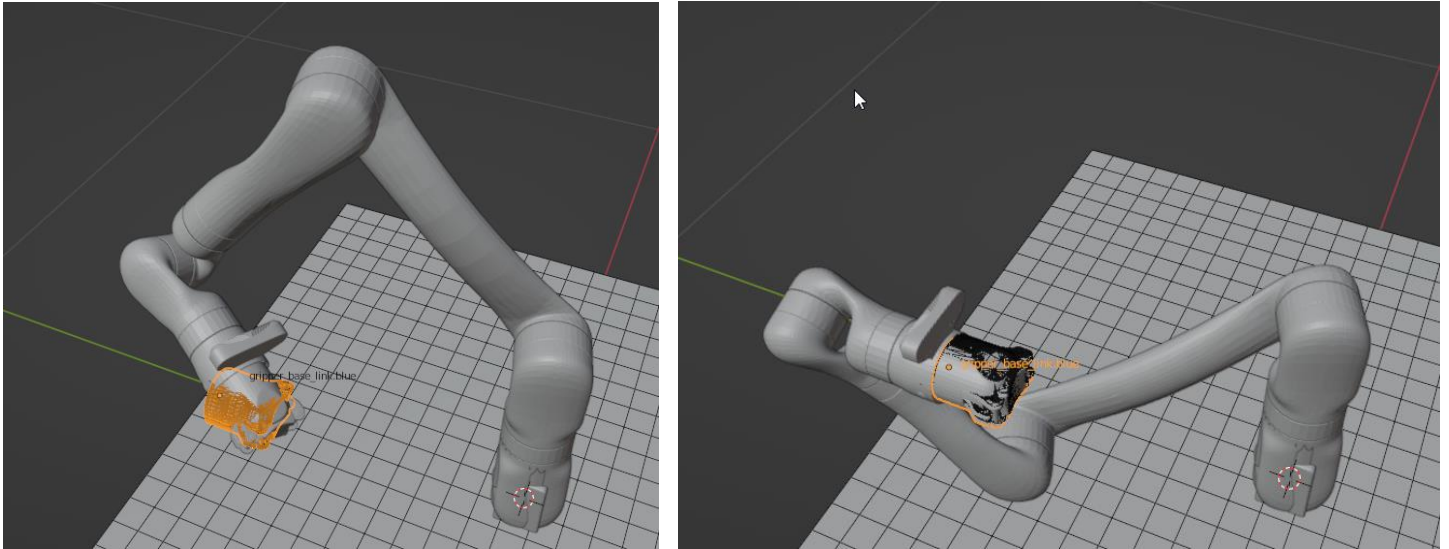
Figure 19. IK Problem, impact of the Local Minimum

Propose a solution to avoid being stuck in a local minimum.

4.6 Hints

You have to complete the code in file robot.cpp,

```cpp
bool
Robot::inverse_kinematic(IKParams& ik_params)
{
  std::vector<float> rpy_in_degrees;
  for(const auto& value: ik_params.rpy_) {
    rpy_in_degrees.push_back(glm::degrees(value));
  }

  logger::info("Target position is ({:g})", fmt::join(ik_params.xyz_, ","));
  logger::info("Target rotation is ({:g})", fmt::join(rpy_in_degrees, ","));

  target_transform_ = glmutil::to_matrix4x4(ik_params.xyz_, ik_params.rpy_);
  float ccd_distance_to_target = std::numeric_limits<float>::max();

  // student code start
```

The "student code" is mainly 3 nested loops:

```cpp
// outer loop on the total number of iterations (from the  --iterations options)
for(size_t i = 1; i <= ik_params.nb_iterations_; ++i) {
  ...
  // middle loop on each non fixed joint
  for(auto ith_ccd_candidate: non_fixed_joint_indexes) {
    Joint& joint = get_ith_nonfixed_joint(ith_ccd_candidate);
    ...
    // inner loop
    // change the angle of the joint between min and max
    // record the angle which minimize the distance
    float best_angle = 0.0f;
    bool found_best = false;

    for(float angle = min_angle; angle < max_angle; angle += angle_step) {
      // set the angle for that joint
      // compute forward kinematic
      // compute the distance of the effector link to target
      // if distance for that angle is less the ccc_distance_to_target, keep that angle
      ...
    } // end inner loop
  } // end middle loop
} // end outer loop
```

To reduce the search space, you can adopt the following strategies:
- The angle_step could change from coarse to fine as the iteration increases.
- The min and max angle can be reduced as the iteration increases. Instead of searching over the full range, a search can be done around the current angle value +/- some percentage.

Rational: The closer the end effector is to the target, the less likely a large change a given joint angle is needed.

5 - Appendix Package Install

This section describes how to install three packages needed for the project:
https://github.com/fmtlib/fmt.git
https://github.com/marzer/tomlplusplus.git
https://github.com/g-truc/glm.git

5.1 Instructions for VS-Code

The libraries must be installed in `%APPDATA%` as you have done in the past using the following instructions, first for `fmt` then for `tomlplusplus`., then for glm
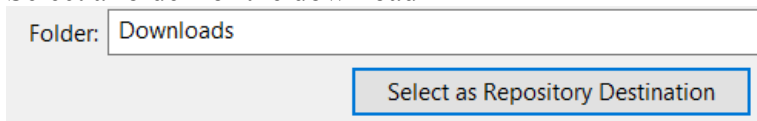
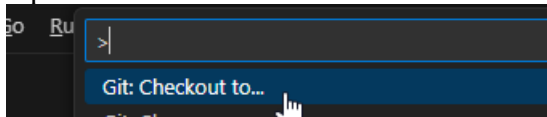Open VSCode, and click on "Clone Git Repository"
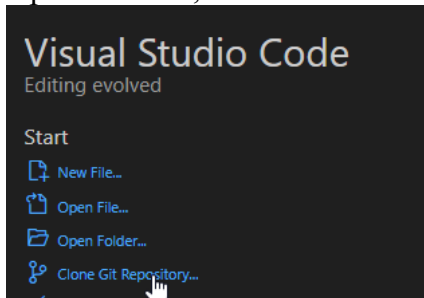
Copy in the URL in the panel
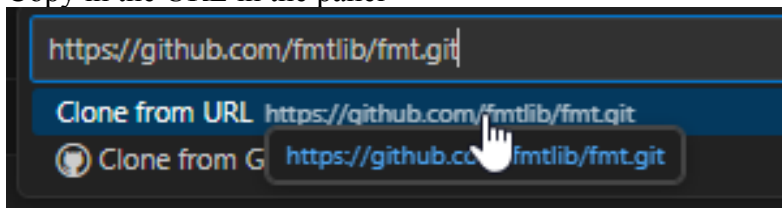
Select a folder for the download

Once the download is complete, the project opens, and you should see the CMake icon

Open the command Palette and select "Git: Checkout to"

Then select version 11.2.0
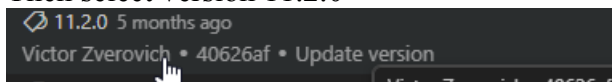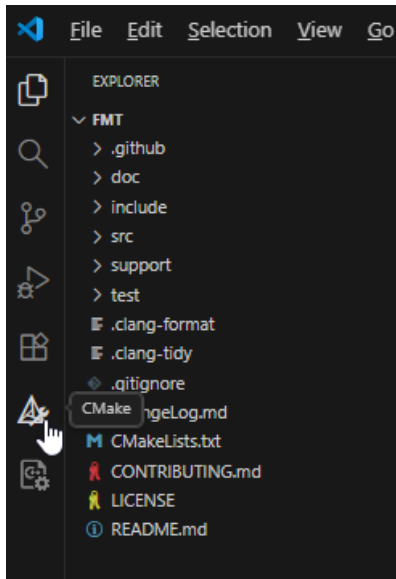
Click on the Extension Setting"
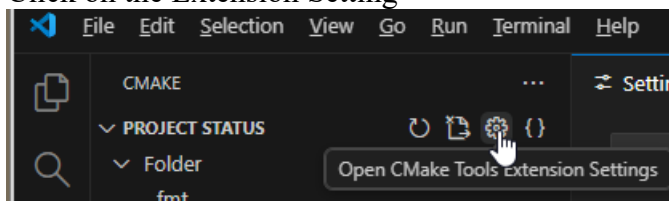
Make sure to set up the *Install Prefix* to **your** value of `%APPDATA%` in tab Workspace
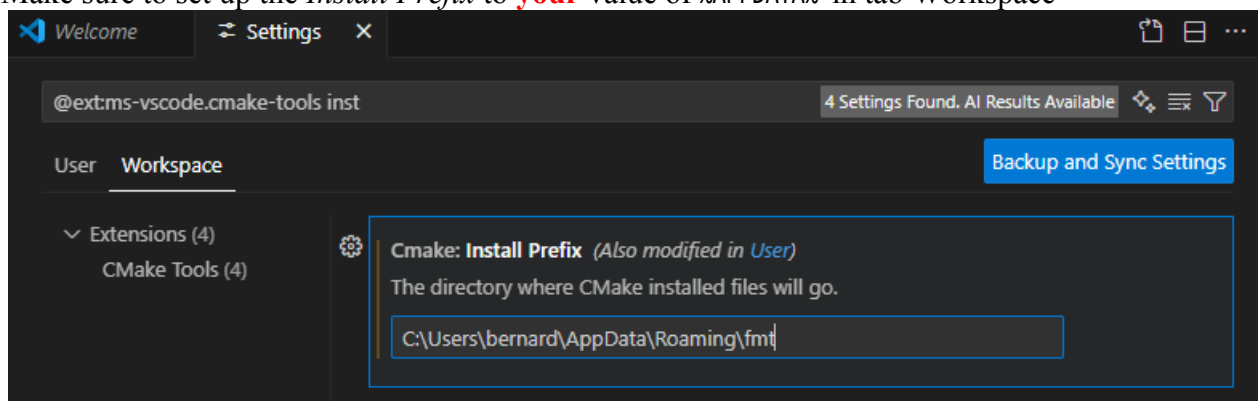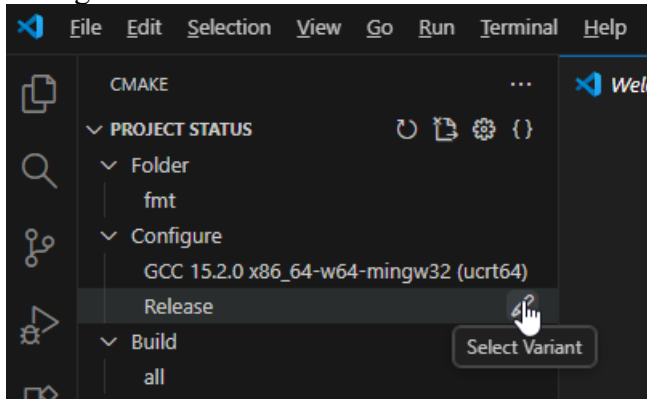

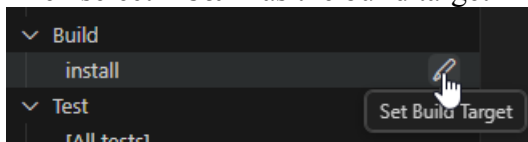Click on it and then click on "*Select a Kit*" in the Configure section
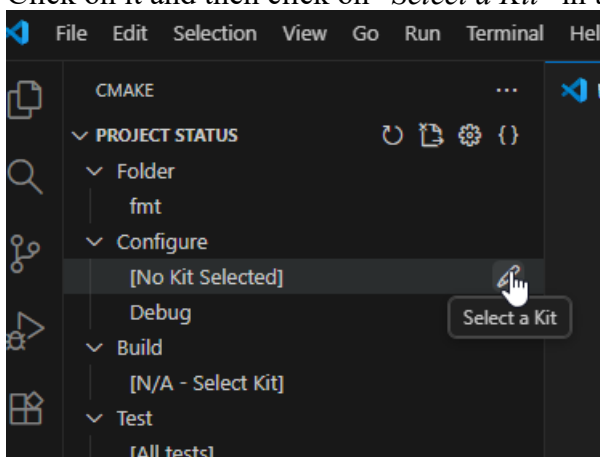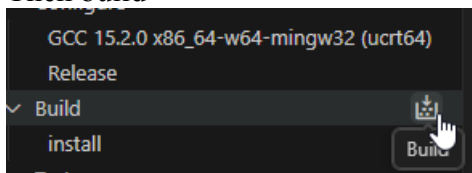

Select the gcc kit
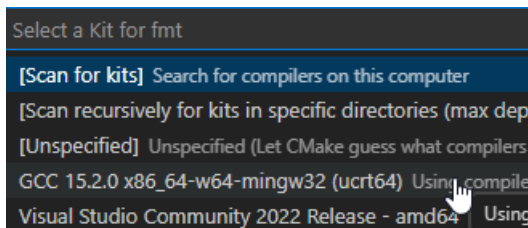
Change the variant to "*Release*"

Then select `install` as the build target
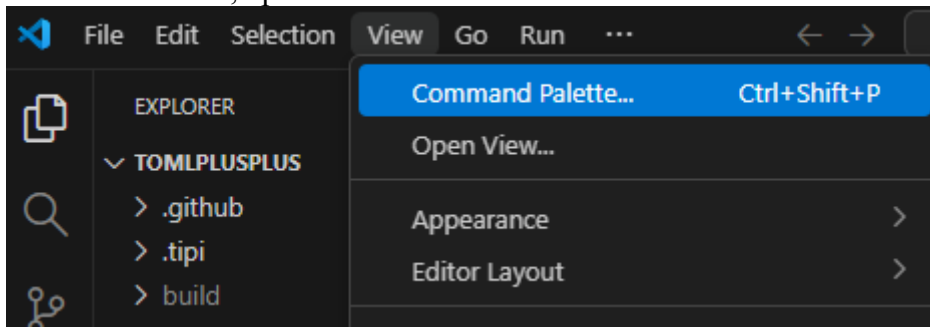

Then build

The build takes about 2 minutes.

Verify that the install is correct by checking the last few lines in VS Code console vs mine:
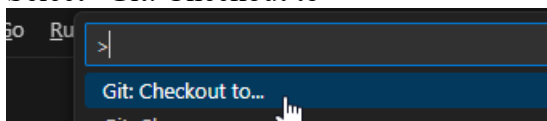
Repeat for TOM

Once the VS Code opens on the project, to the following
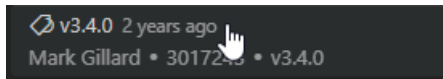
In the view menu, open the command Palette
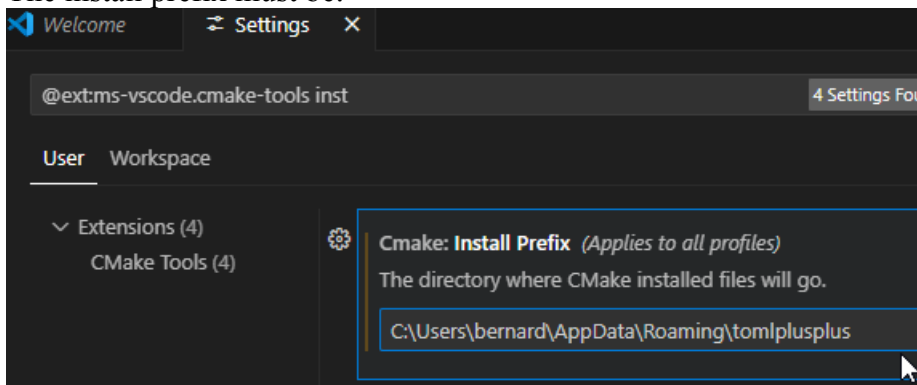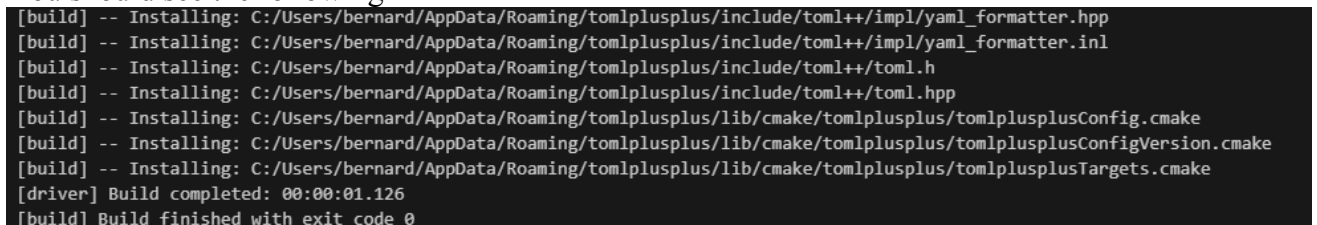

Select "Git: Checkout to"

Then select v3.4.0

Once it's done, you can modify the install prefix
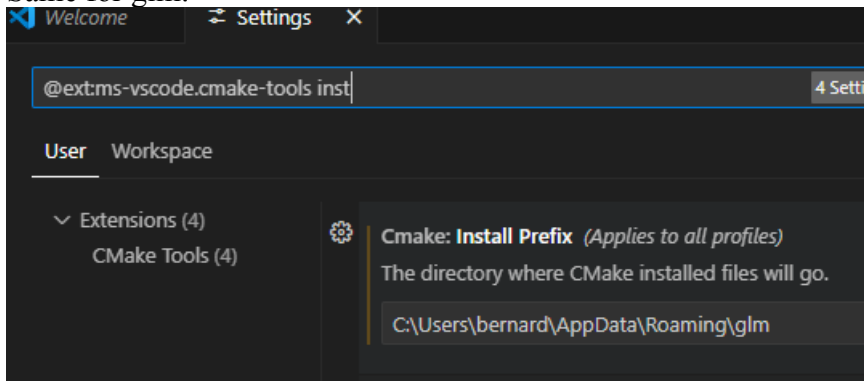
The install prefix must be:

After the build (install target),

You should see the following

```
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/include/toml++/impl/yaml_formatter.hpp
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/include/toml++/impl/yaml_formatter.inl
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/include/toml++/toml.h
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/include/toml++/toml.hpp
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/lib/cmake/tomlplusplus/tomlplusplusConfig.cmake
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/lib/cmake/tomlplusplus/tomlplusplusConfigVersion.cmake
[build] -- Installing: C:/Users/bernard/AppData/Roaming/tomlplusplus/lib/cmake/tomlplusplus/tomlplusplusTargets.cmake
[driver] Build completed: 00:00:01.126
[build] Build finished with exit code 0
```

Same for glm:

Build "install"
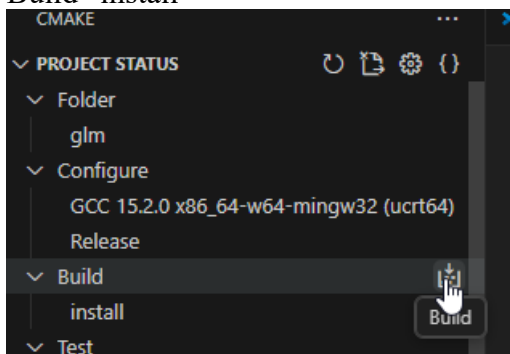
Console should be similar to:

5.2 Instructions for WSL

Open WSL and in a folder of your choice (here I select the home folder), type the following command

```
wsl-shell> cd
wsl-shell> git clone https://github.com/fmtlib/fmt.git
wsl shell> cd fmt
wsl shell> git checkout 11.2.0
wsl shell> cmake -B .build_linux/Release  -DCMAKE_BUILD_TYPE=Release -DBUILD_SHARED_LIBS=TRUE
wsl shell> cmake --build .build_linux/Release -t fmt
wsl shell> sudo cmake --build .build_linux/Release -t install
```

The "cmake fmt" could take up to 5 min
Repeat for toml:

```
wsl-shell> cd
wsl-shell> git clone https://github.com/marzer/tomlplusplus.git
wsl shell> cd tomlplusplus
wsl shell> git checkout 3.4.0
wsl shell> cmake -B .build_linux/Release  -DCMAKE_BUILD_TYPE=Release
wsl shell> sudo cmake --build .build_linux/Release -t install
```
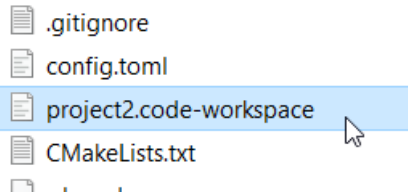
Repeat for glm

```
wsl-shell> cd
wsl-shell> git clone https://github.com/g-truc/glm.git
wsl-shell> cd glm
wsl-shell> git checkout 1.0.1
wsl-shell> cmake -B .build_linux/Release  -DCMAKE_BUILD_TYPE=Release
wsl-shell> cmake --build .build_linux/Release -t glm
wsl-shell> sudo cmake --build .build_linux/Release -t install
```

6 - Install and Test the Project

Extract the content of archive file `ik_package.tar.gz` or `ik_package.zip` to a folder of your choice.

6.1 Instructions for VS Code

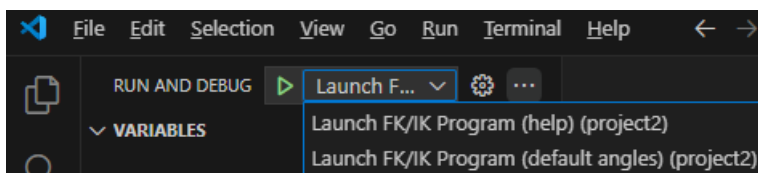Open the VS Code clicking on the file `project2.code-workspace`

And follow the standard CMake processes:

- Select the kit (gcc ...)
- Select the `Release` target
- Build

You are now ready to test the program.

Two launch configurations have been created:

6.2 Instructions for WSL

Open the WSL terminal, and go to the source folder, then build and compile with following two commands:

cmake -B .build_linux/Release -DCMAKE_BUILD_TYPE=Release

cmake --build .build_linux/Release

The result of the build should be very similar to mine

```
wsl shell> cmake --build .build_linux/Release
[ 11%] Building CXX object src/CMakeFiles/robot_kinematic.dir/glm_util.cpp.o
[ 22%] Building CXX object src/CMakeFiles/robot_kinematic.dir/facet.cpp.o
[ 33%] Building CXX object src/CMakeFiles/robot_kinematic.dir/stlmesh.cpp.o
[ 44%] Building CXX object src/CMakeFiles/robot_kinematic.dir/joint.cpp.o
[ 55%] Building CXX object src/CMakeFiles/robot_kinematic.dir/link.cpp.o
[ 66%] Building CXX object src/CMakeFiles/robot_kinematic.dir/poses.cpp.o
[ 77%] Building CXX object src/CMakeFiles/robot_kinematic.dir/robot.cpp.o
[ 88%] Building CXX object src/CMakeFiles/robot_kinematic.dir/main.cpp.o
[100%] Linking CXX executable robot_kinematic
Created /mnt/d/usr/training/C++/labs/inverse-kinematic/project2_student/source.v2/robot_kinematic.exe
[100%] Built target robot_kinematic
```

6.3 Program Execution

Same for VS Code or WSL, at the console prompt, your result must be similar to the one shown below.

6.3.1 Program Help

```
shell> ./robot_kinematic.exe --help
Usage: robot_kinematic [options]
Options:
-h | --help             Display this help
--version               Display the program version
--config     filename   Name of the input robot config file in toml format, default to config.toml
--blender    filename   Name of the output blender script, default to my_script.py
--angles     float,...  The angles of the joints in degrees for FK computation, can be repeated
--xyz        float,...  The target position for IK computation, 3 values
--rpy        float,...  The target rotation for IK computation, 3 values
--method     string     Extra option to enable variants in CCD IK computation
--iterations integer    Number of iterations for the CCD IK computation
--seed       integer    Force the seed used by the random number generator
```

For VS Code you can also use the launch
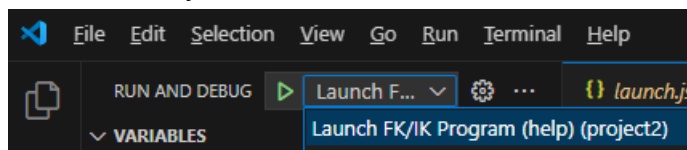
6.3.2 Program With Angle.

- Try now running the program the angles and target options, your output will be very similar to the one below:

```
shell> ./robot_kinematic.exe  --angles -70,-50,90,0,-50,-90 --xyz 0.302,-0.594,0.486 --rpy 0,90,-90
many lines deleted
[INFO]  ++++++++++++++++++++++++++++++++++++++
[INFO]  -------------------------------
[INFO]  --   Start Forward Kinematic   --
[INFO]  -------------------------------
[INFO]  -------------------------------
[INFO]  Compute forward kinematic with angles -70,-50,90,0,-50,-90
[INFO]  ---- FK Student code start here
[INFO]  ---- FK Student code finish here
[INFO]  Target position (x, y, z) = (0, 0, 0)
[INFO]  Target rotation (r, p, y) = (0, 0, 0)

   0,          0,          0}
   1,          0,          0}
   0,          1,          0}
   0,          0,          1}

[INFO]  -------------------------------
[INFO]  --   Start Inverse Kinematic   --
[INFO]  -------------------------------
[INFO]  Using seed 4043503269
[INFO]  Target position is (0.302,-0.594,0.486)
[INFO]  Target rotation is (0,90,-9)
[INFO]  ---- IK Student code start here
[INFO]  ---- IK Student code end here
[INFO]  Final distance after 100 iterations is 3.4028235e+38
[INFO]  Joint angles are (0,0,0,0,0,0)
[INFO]  -------------------------------
[INFO]  --    Write Blender Script      --
[INFO]  -------------------------------
[INFO]  Generate blender script to file my_script.py
[INFO]  Script file generated with 3 poses
```

-

6.4 What's Next

You are now ready to update the two methods in file `robot.cpp`

- `Robot::forward_kinematic(…)`
- `Robot::inverse_kinematic(…)`

6.5 Additional Help

The open graphic mathematic library (GLM for short, found here) provides all the necessary function to perform the matrix operations described in the previous chapter.

Some useful examples:

```
glm::vec4 my_vec(x, y, z, 1.0f);        // create 4D vector
glm::mat4 my_matrix;                    // create a 4x4 matrix initialized to identity
glm::vec4 my_res = my_matrix * my_vec;  // multiply a matrix by a vector
float alpha_d = glm::degrees(alpha);    // convert angle from radian to degree
```