

Example of PhD Thesis with RoboticsLaTeX template



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Declaration of Originality

I, Simone Lombardi, hereby declare that this thesis is my own work and all sources of information and ideas have been acknowledged appropriately. This work has not been submitted for any other degree or academic qualification. I understand that any act of plagiarism, reproduction, or use of the whole or any part of this thesis without proper acknowledgment may result in severe academic penalties.

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On a personal note, I want to thank all my colleagues of the Robotics Engineering course. The friendship I found are extremely meaningful to shape me in the person I am today. Last but not least, in the slightest I want to tell my family and friends that their unwavering support and belief in me did not go unnoticed, I would not be here today if it wasn't for them.

This is a short, optional, dedication. To all the Master and
PhD students of Robotics Engineering at the University of
Genova.

Abstract

Since the 1960s, the use of robotic systems in industrial applications has continuously increased. However, even with this incredible force driving innovation, some tasks have proven to be too complex or not cost-effective to be performed by a robot. With the advent of Industry 4.0, the proposed solution to these problems was **Human-Robot Collaboration** — building work-cells capable of integrating a human agent performing a set of tasks that can be coordinated with a robotic agent to achieve a common objective. This approach opened up a completely new set of challenges, the first of which are safety and perception. The robotic agent needs a way to perceive the human in the workcell and must be able to react to unpredictable movements to avoid collisions. During my thesis, I worked within the **SESTOSENZO project**, specifically in Use Case 1. Their robotic system, composed of two 6-DoF industrial articulated robots mounted in series, is equipped with a set of proximity and tactile sensors. My work focused on creating a unified architecture for the two robots, exploring the capabilities of a 12-DoF robot, and proposing possible directions to improve the system's functionalities. Moreover, this work also aimed to identify potential problems and weaknesses. I achieved these objectives through a series of simulated experiments, using a task-priority approach for system control, as I was interested in exploiting the high redundancy of the robot to perform multiple tasks simultaneously. I then analyzed the result to evaluate the effect of each task on the behavior of the robot.

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Chapter 1

Introduction

Robotic systems from their first introduction in the manufacturing field we relegated to work separated from the human workers. This was because the main use for robots was to perform, highly repetitive tasks, very fast or to work in dangerous environment. This removed the need to have interaction between human and robots. With the advent of industry "3.0" and "4.0" the focus shifted from that to have the robots collaborate with humans to increase efficiency, and to remove some burden from the human worker, especially for physically demanding tasks.

The concept of Human Robot Interaction (HRI) appears in the literature and can be divided in two broad categories, each with their respective challenges.

- **Physical Interaction:** interaction that require or could have some form of contacts with the robotic system.
- **Social Interaction:** interaction that aims to exchange information, or perform conversation of some kind.

In the context of this thesis, and more broadly in industrial applications, the focus is primarily on physical interaction. Collaborative robots operating alongside human workers must function in dynamic environments, where the human agent does not follow predefined trajectories.

As described in [Weidemann *et al.* \(2023\)](#), the **SestoSenso Project** proposes a framework for Human-Robot Collaboration in which controlled physical contact is not only possible but expected. Within this framework, the robot and the human operator jointly manipulate or work on the same object, requiring the robotic system to adapt continuously to

1.1 Research problem and objective

the human's actions. To support this type of collaboration, the robotic platform in the **SestoSenso Project** is equipped with proximity sensors that allow it to perceive changes in its surroundings and react autonomously and in real time. In addition, several robot links are covered with a sensorized tactile skin, enabling the system to detect and interpret physical contact with the environment or with the human collaborator. A key strength and novelty of the SestoSenso robotic setup lies in its multi-stage structure. The complete system features 12 degrees of freedom, created by combining two manipulators: a high-payload industrial arm from KUKA as the first stage, and a lightweight, highly compliant arm from Universal Robots as the second stage. This configuration allows the robot to leverage the strengths of both manipulators—power and precision from the KUKA arm, and flexibility and safety from the UR arm—making it well suited for collaborative tasks.

1.1 Research problem and objective

Since during the **SestoSenso Project** the two robots were controlled separately, in this work, I developed a unified control architecture with the aim to test the capabilities of the complete system in a series of experiments. Specifically with *reaching* and *obstacle avoidance* tasks. All the activities were carried out at MACLAB, the Mechatronics and Automatic Control Laboratory at Università degli Studi di Genova.

1.2 Thesis structure

After the brief introduction in 1 of the objective of this thesis, in 2 I will provide a literature review. 3 is the general description of the control architecture with a focus on the software implementation. In 4 instead the focus will be on the algorithms and methods I used in the architecture. Lastly 5 will be the presentation of the conducted experiments and the conclusion in 6.

Chapter 2

State of the art

In this chapter I will explore the literature on the topics of: *ambient perception* and *avoidance* to explore different approaches to control redundant manipulators in a dynamic environment. During my state of the art research it was apparent a lack of literature on the specific architecture developed in the *SestoSenso project*. For this reason the last part of this chapter has focused more broadly on *high dof architecture*, to explore how long open kinematic chain system are treated, and in which areas are used.

2.1 Environment perception and awareness

Environment perception is one of the biggest difference when we move from the classical use of robotic systems in industry, to a more modern framework geared towards HRI. In this section I reported two of the main method for extracting ambient morphology information from various types of sensors, and explained their strength and weaknesses.

2.1.1 Image recognition based methods

As reported in [Badrloo et al. \(2022\)](#), we can divide vision based methods in two main categories:

- Monocular vision: use a single camera mounted on top of the robot.
- Stereo vision: use two synchronized cameras.

The basic approach of the *visual servoing* with monocular camera can be represented in the following schema:

2.1 Environment perception and awareness

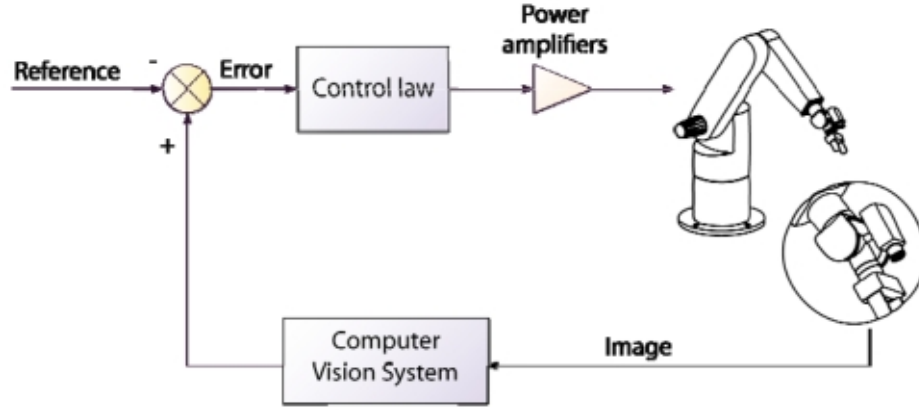


Figure 2.1: Direct visual servoing scheme

In the work of Muslikhin *et al.* (2020) we can see how a monocular system is used with a *deep Region based Convolutional Neural Network* to recognize objects in the field of view of the robot and decide if said object is a target or not. This first step is then followed by a *kNN* and the *Fuzzy interference system* to localize 2D position of the targets, the last coordinate is found by only shifting the end-effector a few millimeters towards the x-axis.

Following and improving the capabilities of a singular camera system there is the use of: stereo vision. Stereo vision works by combining the information of the two cameras, that are placed in a known position to extract information of the third dimension of objects in the images. In the work of Huh *et al.* (2008) we can see how a stereo vision based system is used to perform obstacle recognition on a autonomous driving vehicle.

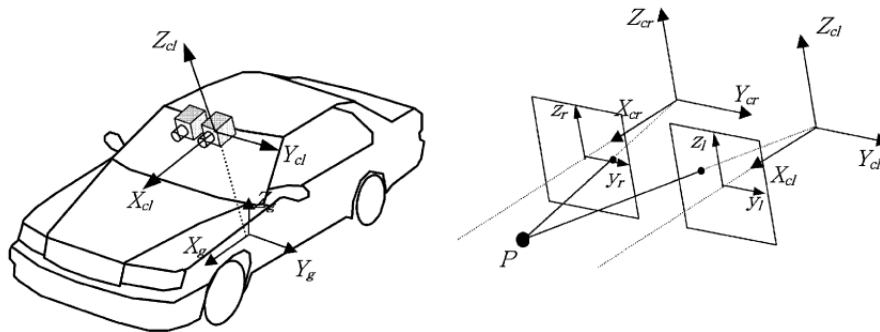


Figure 2.2: Vision coordinate sistem

The image based methods in general appear to have some key char-

2.1 Environment perception and awareness

acteristics that make them impractical for effective *obstacle perception* in an environment such as the one of the **SestoSenso project**.

With the advent of AI in recent years the use and potential of *image recognition* and with it all the vision based systems has greatly increased. But they still have a series of weaknesses that have a large impact when it comes to develop viable systems for industrial application. In the work of [Panasiuk \(2025\)](#) a control system using a 3d stereo camera and the YOLO AI algorithm for image recognition, those limitation are evident:

- **Hardware and software:** The cost of the system parts is not paltry, from the camera to the AI software.
- **Integration and configuration:** The camera apparatus has an implementation that is task-specific, which means that every change in the environment requires a complete re-configuration of the system.
- **Computational cost:** The image analysis is performed on a separated computer to manage the burden of the computation.
- **Field of view:** The camera visualize only the work area, which is not adequate for a HRI situation.
- **Environment interference:** The use of 2D and 3D image information, require to have a strict control on the occlusion and disturbances in the environment, from lighting to airborne dust. This level of control is not possible in a industrial context.
- **Privacy:** One problem not addressed by the paper is the privacy of people working around or with the robot, that is not maintained with the use of a camera.

2.1.2 Point-cloud discretization based methods

In the work of [Zauner et al. \(2025\)](#) three different type of spatial perception sensor are evaluated to create point cloud of a robot's workspace. To perform safe navigation and avoid collisions. the sensor used are:

- **Time Of Flight:** *Kinect V2* and *Omron OS32C Lidar*
- **Active Stereoscapy:** *Intel RealSense D435*

The two time of flight sensor work with a infrared light and a laser respectively and the measure the distance from an object by timing the time delta at the reception of the light impulse. The Intel sensor instead is based on the *stereo vision* principle, but it uses simpler cameras aided by a infrared projector that imposes a grid of points onto the surfaces. The sensors are mounted on the *end effector* of the manipulator and panned over the workspace to record a sample of the environment, the resulting pointcloud is then processed to reduce the number of points and to extract feature of the environment.

In the paper the extracted feature are used to simplify the 3D representation of the obstacle, and to perform collision-checks they confronted a series of different algorithms. In the case of my thesis I stopped after the filtering to reduce the number of points, then the point cloud is directly used to represent the robot and obstacle in the simulation.

As stated in [Husmann et al. \(2008\)](#) the main drawback of *ToF* sensors is the lower resolution capabilities in comparison to *stereo vision* techniques. The paper highlight that even with this performance deficit the *ToF* were viable to be used in automotive application even for safety tasks.

2.2 Obstacle avoidance in HRC

For *Human-Robot Collaboration* applications, the robot must operate under a *multi-objective* control strategy, where the system handles a *goal-driven task* defining the role of the robot, and one or more other task that go from safety to optimization tasks. Within collaborative scenarios, the safety layer must be treated with **higher priority**, temporarily overriding the main objective whenever a hazardous situation is detected, to guarantee human and system protection in real time. In this thesis, the prioritized secondary objective ensuring safe collaboration is *obstacle avoidance*, which monitors the robot surroundings and generates motion corrections when the robot is too close to the obstacle.

In the case of a manipulator arm we have to also include the z axis, since we are operating in 3d space. Looking at the work of [Zhang & Sobh \(2003\)](#) we can see how we can compute a safe trajectory for a *SIR-1* robot manipulator using cubic polynomials for a path with intermediate points. In this paper is interesting the introduction of the concept: *link collision avoidance*. By controlling the *link* closest point to the obstacle and using the analytical formulation of the *Inverse Kinematics* and the *obstacle shape* it is possible to define *joint variables* constraints to

ensure a collision free navigation.

In the work of: [Maciejewski & Klein \(1985\)](#) instead the proposed approach considers the closest point of the hole robot to the obstacle, than it apply a velocity vector to said point that is directly opposite to the distance vector $(P_{ob} - P_{rb})$.

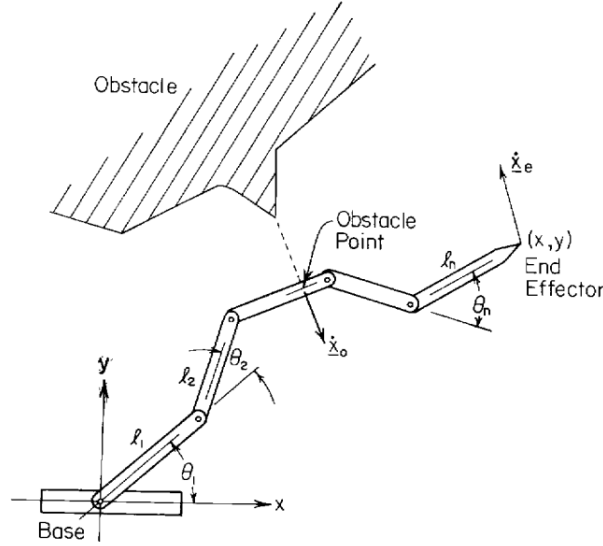


Figure 2.3: Obstacle avoidance schema

To ensure that the *obstacle avoidance* desired velocity does not impact the tracking of the *end effector velocity* the joint space velocity are searched in the null-space of the solution to the first problem. This approach allows to leverage the redundancy of the manipulator. The proposed algorithm is then applied to a planar robot with parallel *revolute* joints, as shown in the image. And also to a 3D redundant manipulator operating through the window of an automobile door.

2.2.1 Redundancy control

From the discussion of the previous section it is clear that to correctly perform obstacle avoidance the control architecture has to deal with multiple objectives. This objective need to be *task oriented* to allow for portability between different system configuration. The classic framework for this type of control was developed by [Slotine & Siciliano \(1991\)](#) and extended by [Simetti & Casalino \(2016\)](#) to include the activation and

2.3 High DoF architecture

deactivation of task without discontinuities. The general idea is to have a *hierarchy of tasks*, defined to be *objective specific* and not connected to the particular structure of the robot. Given a generic objective function defined in the task space:

$$\dot{\mathbf{x}}_i = \mathbf{J}_i(q) \cdot \dot{\mathbf{q}} \quad (2.1)$$

- $\dot{\mathbf{q}} \in \mathbb{R}^{(n \times 1)}$: joint displacement vector.
- $\dot{\mathbf{x}}_i \in \mathbb{R}^{(m_i \times 1)}$: task velocity vector, or *reference rate*.
- $\mathbf{J}_i(q) \in \mathbb{R}^{(m_i \times n)}$: task jacobian matrix.

Given that the solution of the highest priority task is:
 $\dot{\mathbf{q}}_1 = \mathbf{J}_1^\# \dot{\mathbf{x}}_1 + (\mathbf{I} - \mathbf{J}_1^\# \mathbf{J}_1) \dot{\mathbf{z}}$, $\forall \dot{\mathbf{z}}$ the second part of the solution is the projector on the *null space* of \mathbf{J}_1 , the solution to the lower priority task are searched in that space. Yielding the general solution:

$$\dot{\mathbf{q}}_i = \dot{\mathbf{q}}_{i-1} + \mathbf{J}_i(\mathbf{I} - \mathbf{J}_i^\# \mathbf{J}_i)(\dot{\mathbf{x}}_i - \mathbf{J}_i \dot{\mathbf{q}}_{i-1}) \quad (2.2)$$

In the paper is demonstrated that the solution of a lower priority task does not modify the higher one, but it is *attempted* in the null space.

2.3 High DoF architecture

In this section I want to explore some of the relevant high-dof architecture found in the literature.

2.3.1 Dual-arm systems

In recent years there has been a trend to use these dual-arm systems for HRC(Human Robot Collaboration), but also for replacing human workers without the need to redesign the work cell.



Figure 2.4: Dual-arm industrial robot example, SDA10

As is stated in the survey of [Smith et al. \(2012\)](#) the strengths of the dual arm architecture are:

- *Similarity to operator*: useful both in the case of HRC and to substitute the human worker with minimal effort.
- *Flexibility and stiffness*: Combining the stiffness of closed chain manipulation, with the flexibility of a serial link.
- *Manipulability*: High number of DoFs allows for complex motion tasks.
- *Cognitive motivation*: The similar characteristics of the kinematic chain is believed to be helpful in HRC context.

In most cases for these architectures the *obstacle avoidance* is computed for the *navigation* if the robot has a movable base. Moreover the interaction with the environment is performed with the use of *visual servoing*, which was firstly discussed by [Hutchinson et al. \(2002\)](#), position based and *hybrid* methods, combining visual and position information.

2.3.2 Snake-like robot

A completely different class of robot is represented by the "snake like" robot. As shown in the work of [Hirose & Yamada \(2009\)](#) and [Crespi et al. \(2005\)](#) these types of robot are biologically inspired, and they can

2.3 High DoF architecture

produce a forward motion from an undulatory one. Reproducing the movement patterns of snakes.



Figure 2.5: snake like robot from [Crespi et al. \(2005\)](#)

The potential of these robot that are currently being explored are for navigation in tight spaces, to be applied to endoscopes for examples. In addition the interest lies in the flexibility of a "snake like" body, since it could be used to move, climb and grasp if needed.

2.3.3 Planar robot

For more industrial application, I reviewed the work of [Le Boudec et al. \(2006\)](#) and [Maciejewski AA \(1985\)](#). These work take into consideration high-dof planar manipulator, and they also propose two approaches to do *Obstacle avoidance* with their respective architecture. In the case of [Le Boudec et al. \(2006\)](#) the paper uses the ANAT robot, presented in the figure below.

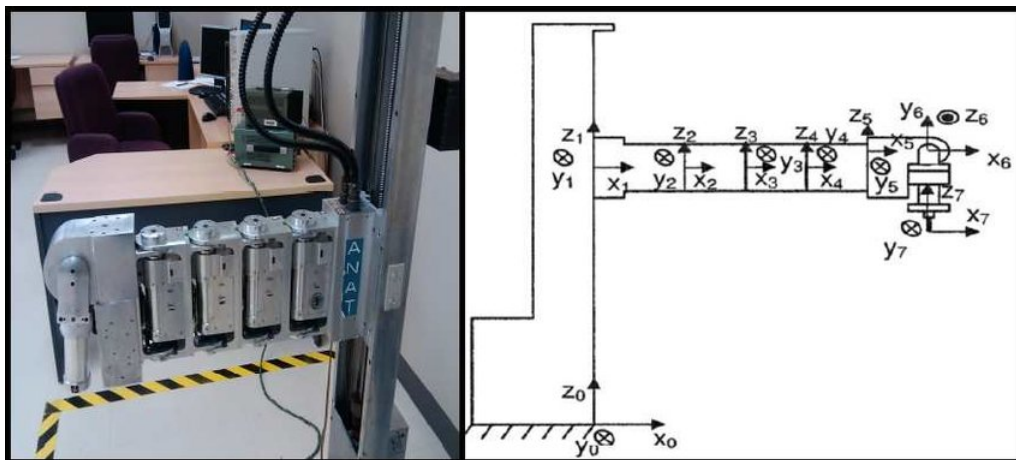


Figure 2.6: ANAT robot arm

2.3 High DoF architecture

This is a 7Dof robot, comprised of 1 *prismatic* joint to control the z coordinate, followed by 3 parallel *revolute* joints and a 3 Dof *wrist*.

The proposed control algorithm is based on the work of Zlajpah (1997) for the computation of the generalized inverse of the jacobian matrix. In addition, the obstacles are modeled as hyper planes to reduce computational costs and the control law is applied to the joints in order. In this paper the proposed method is applied at the *Dynamic* level, the objective function for the *Obstacle avoidance* is computed as follows:

$$V_1(q) = \sum_{i=1}^m \sum_{j=2}^n \frac{\alpha_{ij}}{-\left(\frac{x_j - x_{ci}}{r_i + r_{si}}\right)^2 - \left(\frac{y_j - y_{ci}}{r_i + r_{si}}\right)^2 - \left(\frac{z_j}{h_i + h_{si}}\right)^2 + 1} \quad (2.3)$$

where:

- m, n : respectively the number of obstacles, and the number of points placed on the robot.
- α_{ij} : weight of the constraint for joint i from obstacle j
- (x_j, y_j, z_j) : coordinates of joint j in the *base frame*
- $(x_{ci}, y_{ci}, r_i, h_i)$: coordinates of cylinder i in the *base frame*
- (r_{si}, h_{si}) : safety distances in *radius* and *height* from cylinder j

The approach generates a *repulsive force* that becomes stronger as the robot approaches an obstacle. While *potential-field techniques* are a standard choice for *dynamic obstacle-avoidance control*, I could not adopt them in this work because the robots' *dynamic controllers* were locked behind the manufacturer's proprietary software, preventing access to the required control layer.

2.3.4 Macro Micro configuration

The last interesting configuration I want to talk about is referred in the literature as *Macro-Micro Robot*. Firstly proposed by Sharon & Hardt (1984), the objectives of the proposed architecture were to resolve the opposing problems of *speed* and *tracking precision* and also to correct the errors in *end point measurement*, given by bending in the links and errors in the measurement errors in the encoders.

2.3 High DoF architecture

The uses and capabilities of this configuration are presented in the work of Zhou *et al.* (2022), following is a photo of the robot they used.

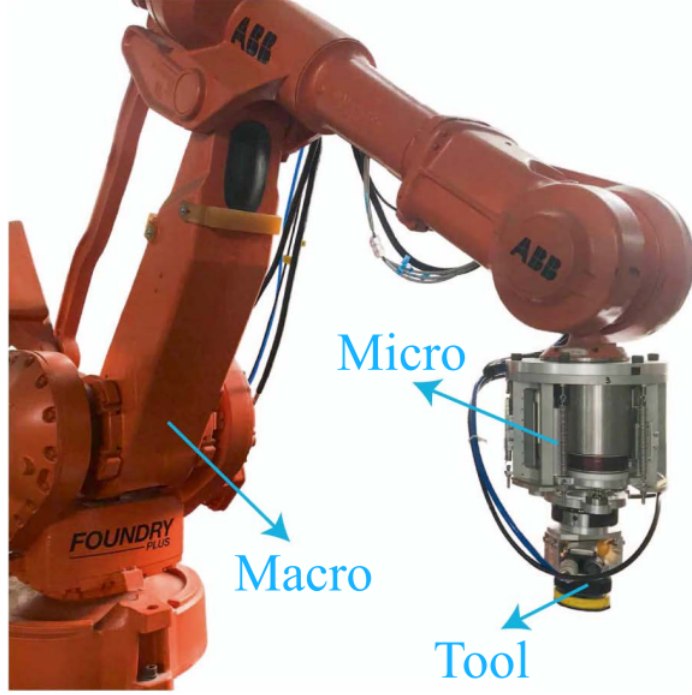


Figure 2.7: Macro-Micro robot

The robot is composed of a 6 Dof *Macro* manipulator and a 3 Dof *Micro*. The robot is equipped to perform polishing tasks on complex surfaces.

The paper focus is to prove the effectiveness of a *sampling based* motion assignment(MA) strategy with multi performance optimization. Since the robot has a total of 9 degree of freedom there is space for optimization in the robot movement. The configuration optimization function is to be minimized for each sampling point of the chosen trajectory, and for each point the performance index and constraint ($RPI_{c,i}(q)$) must be computed. Classic *gradient based* methods can easily stop at local minima since the function is not convex, the proposed MA aims to optimize the movement of macro and micro manipulator, avoiding the costly and error-prone computation. The system on which I worked on this thesis is of the same general structure, but the two robot are considered as a whole. Also in my work I am not computing any offline trajectory as in the case of this paper.

2.3 High DoF architecture

Another application of the *Macro-Micro* configuration is in the field of medical robotics, in the work of [Cursi et al. \(2022\)](#). In this paper the proposed architecture is composed of a *KUKA LBR IIWA* robotic arm with 7 Dof, and a *Micro-IGES* surgical robotic instrument with 7 Dof(2 Dof are composed of the jaws of the instrument).

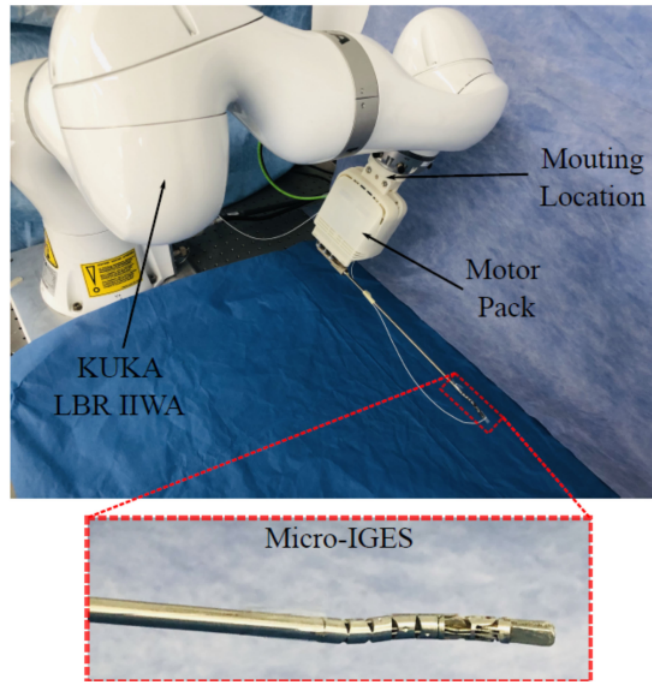


Figure 2.8: Macro-Micro surgical robot

In this paper the objective was to demonstrate that the overall performance of the system can be improved by defining preoperatively the best initial configuration of the surgical instrument in terms of *roll*, *pitch* and *yaw* with respect to the macro serial-link manipulator to achieve maximum accuracy in performing specified tasks. The paper highlights how the macro micro manipulator configuration allows for completion of multiple-objective tasks, such as:

- *Guarantee Remote Center of Motion*: The RCM(which for surgical application is usually the incision site) has to remain stationary.
- *Desired path tracking*
- *Assembly errors compensation*

2.3 High DoF architecture

The method used in this paper starts with a *Genetic algorithm* used to generate possible configuration, that are then evaluated through *Hierarchical Quadratic Programming*. The solution of the procedure finds the best initial configuration based on a fitness function and resilience to errors.

Chapter 3

Architecture implementation

3.1 System Description

The robotic system I worked with was composed of two articulated industrial robot, namely a **Kuka KR150** from *Kuka* and a **UR10e** form *Universal Robot*.

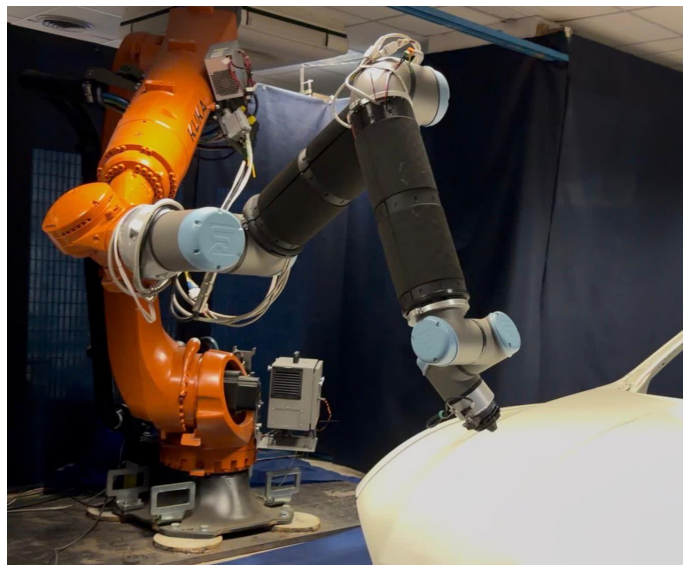


Figure 3.1: photo of the real system, inside the workcell

I started the from the work done by the team at MACLAB, and since their code already included the simulation part, I opted to incorporate their work in my architecture.

3.2 JointRobotTP Class Implementation

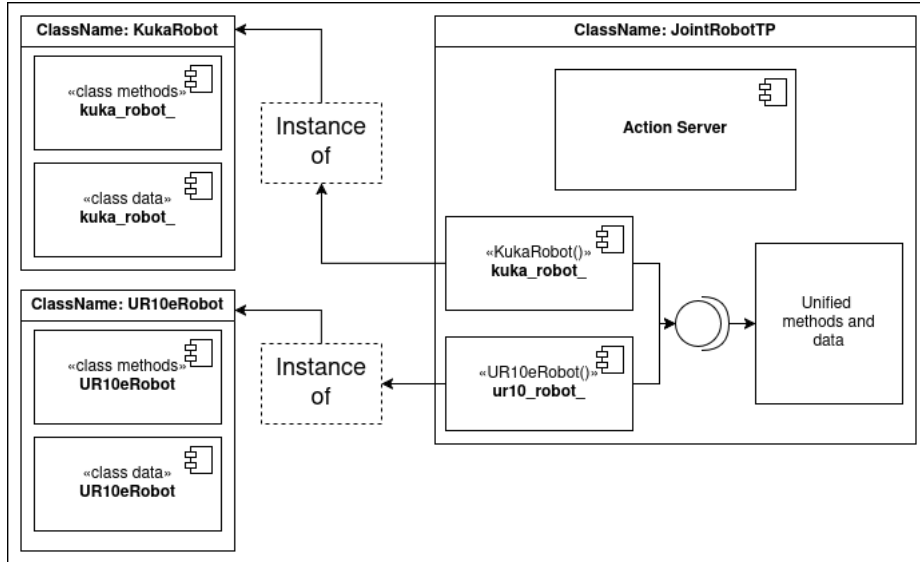


Figure 3.2: Simplified structure of the class JointRobotTP

The main objective was to use the existing classes developed for the single robots, and incorporate them in the unified architecture. The goals I wanted to pursue were the following:

1. Have an efficient way to send commands to the unified robot.
2. Use data structure that allowed me to add and remove tasks and configuration easily.
3. Keep a degree of separation between the robot representation and the control algorithm.

In the following section I will describe more in detail the structure of the *JointRobotTP* class.

3.2 JointRobotTP Class Implementation

The main part of the implementation of the class, are:

1. custom Action Server **RobotMoveTP**, implemented in the `uc1_robot_controllers_interfaces` package.
2. The two data structure used for the initial configuration reaching `initial_configurations_map_` and `TP_task_map_` to compute and store the matrix relative to each tasks.

3.2 JointRobotTP Class Implementation

3. The class used to compute each "step" of the task priority algorithm.

3.2.1 Action server

The custom message definition for the Action server I used to send goals to the robot is as follows:

```
(<pkg> : uc1_robot_controllers_interfaces)
```

```
<pkg>/MoveRobotGoal      goal
    string                init_config_name
    -----
    string                result
    -----
    float64               linvel_norm
    float64               angvel_norm
```

and the custom message defined for the action goal is:

```
<pkg>/MoveRobotPoint      translation
                           float64    x
                           float64    y
                           float64    z
<pkg>/MoveRobotOrient      orientation
                           float64    roll
                           float64    pitch
                           float64    yaw
```

The goal is sent from the user as a *translation* and *rotation* relative to the initial position of the end-effector(in this case I am referring to the end-effector of the *UR10e* which is the end-effector of the unified robot). The action server then uses the information from the two robots to broadcast the *Goal* with respect to the *Kuka base link*. For each *Goal* received by the robot, I can set a different *Initial configuration*. The field called `init_config_name` uses a map defined inside the class to set the robot in a specific configuration before starting the *Reaching loop*.

```
std::map<std::string, Eigen::VectorXd>    init_config_name
```

By using this data structure I can use the field of the goal message to directly select the desired initial configuration. The set of initial configuration is defined to have interesting starting position of the robot, to analyze different behavior of the robot in the experiment part.

3.2 JointRobotTP Class Implementation

3.2.1.1 Action Server process flow

Here is a flow chart to better explain the functionalities of the action server implemented in the *JointRobotTP* class:

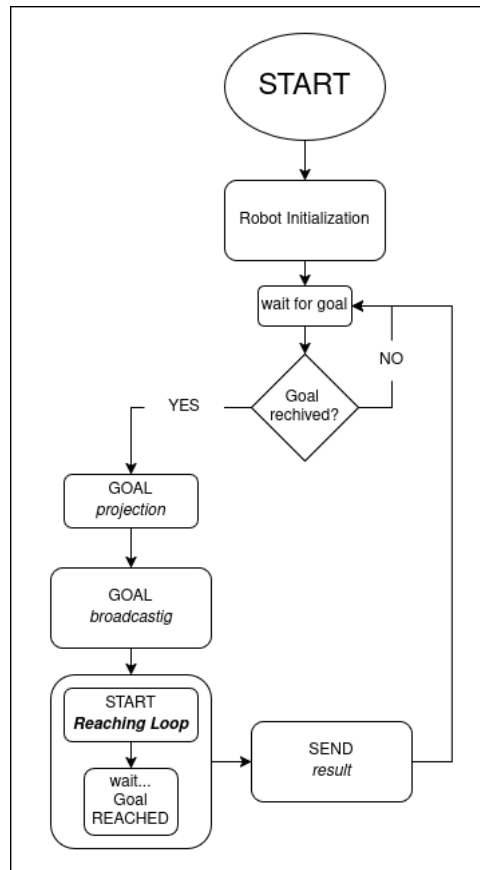


Figure 3.3: Action server flow chart

The method handling this loop is called:

```
void execute(const std::shared_ptr<MoveRobotTP> goal_handle);
```

after receiving the goal and accepting it, the requested goal is projected in the *Kuka robot base* and then broadcasted in the simulation. Lastly the method call for the *Reaching loop*, which I will explain in the next section.

3.2.2 Task Priority implementation

The control part is composed of two separate part: the data part, which is a member of the *JointRobotTP* class as for 3.2. This part is composed

3.2 JointRobotTP Class Implementation

of a map `TP_task_map_` that contains all the matrixes relative to each task. A set of three function that are used to update the information inside the *Reaching loop*.

The definition of the data structure:

```
std::map<std::string, tp_task> TP_task_map_;
```

and `tp_task` is a `struct` with the following fields:

```
Eigen::MatrixXd RefRate;  
Eigen::MatrixXd ActMatrix;  
Eigen::MatrixXd TskJacobian;
```

Secondly the set of functions for updating the information in `TP_task_map_` for each task have the structure:

Type	Name	Args
<code>void</code>	<code>Update_TRR_<task_name></code>	<code>void</code>
<code>void</code>	<code>Update_AFunc_<task_name></code>	<code>void</code>
<code>void</code>	<code>Update_TskJac_<task_name></code>	<code>void</code>

The *Task Priority* control part is implemented trough a separate class. This class, called: `TPComputation`, has as private members two matrixes,

```
Eigen::MatrixXd Q;  
Eigen::MatrixXd ydot;
```

these matrixes are the **projector** and the \dot{y} of the last computed "step". Also in the initializaiton step i can define the values for the constants used in the computation of the pseudo-inverse matrix, these values will be described in 4.

As public members this class has methods to call for computing the *Task Priority algorithm*, task by task. The priority is imposed by the calling order in the *Reaching loop* code. These methods are structured as follows:

3.2 JointRobotTP Class Implementation

Type	Name	Args
void	init_TPComputation	int Ndof, float lambda, float weighth, float treshold
void	computeTP_step	Eigen::MatrixXd ActFunct, Eigen::MatrixXd TskJacobian, Eigen::MatrixXd RefRate
Eigen::MatrixXd	getTP_ydot	void

3.2.2.1 Reaching loop process flow

Finally I include a flow chart to inform about the process behind the *Reaching loop* implementation, for reference to the entire architecture [3.3](#).

3.2 JointRobotTP Class Implementation

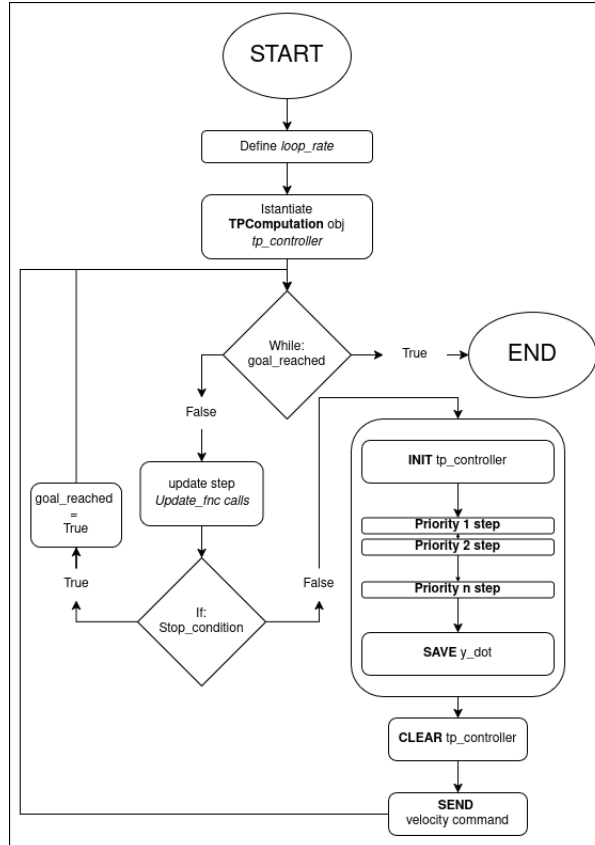


Figure 3.4: Reaching loop flow chart

The method used to implement this loop is one of the public member of the *JointRobotTP* class, namely:

```
void RunCartesianReachingLoop(std::string goal_frame, bool
reached_goal)
```

In the *Update step*, all the function created that are relative to a *task* are called, starting with the *Reference Rate*, *Activation function* and lastly *Task Jacobian*. The second part, the *Stop condition* is checked. If the control is positive the loop is immediately stopped, and the result is

3.2 JointRobotTP Class Implementation

sent to the action server client. Next the *tp_controller* is initialized, the variables for the pseudo-inverse are initialized in this step. Than each "step" of the algorithm is computed, finishing with a "null" task, composed of two Identity matrix for *Activation function* and *Task Jacobian*, and with a zero vector for *Reference Rate*. The loop is repeated until the condition is met.

Chapter 4

Methodology

in this chapter I will describe in detail the mathematical computation performed by the control algorithm I developed.

4.1 Goal broadcasting

The architecture works in a *position reaching* framework, a goal position for the *end effector* is sent to the robot and the algorithm tries to reach said position, with constraint given by other tasks. The goal is sent using the *action server* build in the *JointRobotTP* class, in the form of two vectors:

$$\mathbf{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} ; \quad \boldsymbol{\rho} = \begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix} \quad (4.1)$$

The first represent the desired translation, and the desired rotation as *roll*, *pitch*, *yaw* angles. The projection frames of this vector to define the goal position and orientation could be either the *end effector* frame, or, the *kuka base* frame. This was done for experimental purposes, for easily sequencing different goals, or to repeat reaching tasks to a specific position in the environment.

For the orientation of the goal, $\boldsymbol{\rho}$ is used to compose the rotation matrix that is then projected on the desired frame:

$$\mathbf{R}_{goal} = \mathbf{R}_z(\psi) \cdot \mathbf{R}_y(\theta) \cdot \mathbf{R}_x(\phi) \quad (4.2)$$

$$\langle kuka_base \rangle : {}^{kb}\mathbf{R}_{goal} = \mathbf{I} \cdot \mathbf{R}_{goal} \quad (4.3)$$

$$\langle end_effector \rangle : {}^{ee}\mathbf{R}_{goal} = \mathbf{R}_{ee}^{kb} \cdot \mathbf{R}_{goal} \quad (4.4)$$

In the first case the projection matrix is the identity since $\langle kuka_base \rangle \equiv \langle world \rangle$. Same process is done for the translation vector:

$$\langle kuka_base \rangle : {}^{kb}r_{goal} = \mathbf{0} + r_{goal} \quad (4.5)$$

$$\langle end_effector \rangle : {}^{ee}r_{goal} = r_{ee}^{kb} + r_{goal} \quad (4.6)$$

Then the rotation matrix and the translation vector are use to publish the $\langle goal \rangle$ in rviz.

4.2 Task Priority

Continuing the discussion from 2.2, the classic task priority algorithm as explained in Simetti & Casalino (2016) lacks the ability to smoothly activate and deactivate *inequality* task when the robot is far from the activation region. The approach that I implemented is based on the definition of a new *regularized pseudo-inversion operator* that integrates the *activation function* as a weight matrix to modulate the intensity of the action taken for a specific task. The operator is defined as:

$$X^{\#,A,Q} \triangleq (X^T A X + \eta(I - Q)^T(I - Q) + V^T P V)^{\#} X^T A A \quad (4.7)$$

where the matrix V is the right orthonormal matrix of the SVD decomposition for $X^T A X + \eta(I - Q)^T(I - Q)$. The compact expression of the algorithm becomes, for the k -th priority level:

$$\begin{aligned} W_k &= J_k Q_{k-1} (J_k Q_{k-1})^{\#,A_k,Q_{k-1}} \\ Q_k &= Q_{k-1} (I - (J_k Q_{k-1})^{\#,A_k,I} J_k Q_{k-1}) \\ \rho_k &= \rho_{k-1} + Q_{k-1} (J_k Q_{k-1})^{\#,A_k,I} W_k (\dot{x} - J_k \rho_{k-1}) \end{aligned} \quad (4.8)$$

4.2.1 Task Description

4.2.1.1 Minimum altitude

4.2.1.2 Obstacle Avoidance

4.2.1.3 End Effector Target

Chapter 5

Experiments

5.1

Chapter 6

Conclusions

Write the conclusions here...

Appendix A

Extra

Write here...

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