INDUSTRIAL IMPLEMENTATION OF A PATH PLANNING ALGORITHM WITH DYNAMIC OBSTACLE AVOIDANCE FOR SAFE HUMAN-ROBOT COLLABORATION

by

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B.S., Mechanical Engineering, İstanbul Technical University, 2017

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Mechanical Engineering
Boğaziçi University
2020

ACKNOWLEDGEMENTS

Completing this thesis would not be possible without the help of my supervisor, Prof. Evren Samur. I sincerely thank him for his valuable support and guidance throughout my study. I would also like to thank Prof. Şeniz Ertuğrul and Prof. Sinan Öncü for accepting to take part in the jury of my thesis despite their busy schedule.

I want to thank HKTM A.Ş. for giving me an opportunity to be a part of their R&D team. I also want to express my gratitude to Tolga Cankurt and Ali Kutlu from HKTM A.Ş. for their help throughout project with their priceless expertise.

I would like to thank Boğaziçi University Haptics & Robotics Lab members Burcu, Şeref, Bora, Taylan, Uğur, Kübra, and Günay for their help and company. Last but not least, I would also like to express my deepest gratitude to my family for their unconditional love and support.

This project is supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK TEYDEB #1170213).

ABSTRACT

INDUSTRIAL IMPLEMENTATION OF A PATH PLANNING ALGORITHM WITH DYNAMIC OBSTACLE AVOIDANCE FOR SAFE HUMAN-ROBOT COLLABORATION

Industrial robots are programmable, controllable, and multifunction machines having superior movement capabilities compared to conventional manufacturing equipment. They are commonly used in various production applications such as assembling, material handling, and machining. Due to their high production rate and ability to work in severe conditions, the usage rate of industrial robots has been increasing rapidly. Although a production line can be robotized considerably, existence of human operators is a significant factor in terms of efficiency. The idea of humans and robots coexisting in robotic manufacturing environments has increased the importance of personnel safety. Therefore, a concept called human-robot collaboration has emerged and expanded to the industrial applications. While developing systems for human-robot collaboration in industrial environments, some limitations are encountered. For instance, traditional industrial robots are generally programmed to follow predefined paths which makes it impossible to adapt the robots to changing environments. In this thesis, which is set out to come up with a solution to this adaptation problem, an industrial robotic system supporting human-robot collaboration with an ability to work in a changing environment is proposed. The system is composed of four main parts: an industrial pick and place process with a conveyor and an industrial robot, human information system with a projection, detection system with a laser scanner, and control and communication components. The proposed system is realized, and experiments for testing the performance of the system are carried out. The results indicate that the response of the system is encouraging for safe human-robot collaboration in industry.

ÖZET

GÜVENLİ İNSAN-ROBOT İŞBİRLİĞİ İÇİN DİNAMİK ENGEL KAÇINMA İÇEREN BİR YÖRÜNGE PLANLAMA ALGORİTMASININ ENDÜSTRİYEL UYGULAMASI

Endüstriyel robotlar, geleneksel üretim ekipmanlarına göre üstün hareket kabiliyetine sahip programlanabilir, kontrol edilebilir ve çok işlevli makinelerdir. Montaj, malzeme taşıma ve talaşlı imalat gibi birçok üretim uygulamasında yaygın olarak kullanılırlar. Yüksek üretim oranı ve zor koşullarda çalışma kabiliyetlerinden dolayı endüstriyel robotların kullanımı hızlı bir şekilde artmaktadır. Bir üretim hattı yüksek ölçüde robotlaştırılabilse de, insan operatörlerin varlığı verimlilik açısından önemli bir faktördür. Robotik üretim ortamlarında bir arada çalışabilen insan ve robot fikri, personel güvenliğinin önemini artırmıştır. Bu nedenle, insan-robot işbirliği adı verilen bir kavram ortaya çıkmış ve endüstriyel uygulamalara da yayılmıştır. Ancak, endüstriyel ortamlarda insan-robot işbirliği için sistemler geliştirilirken birtakım sınırlamalarla karşılaşılmaktadır. Örneğin, geleneksel endüstriyel robotlar, önceden belirlenen yörüngeleri takip edecek şekilde programlandırılmaktadırlar ve bu durum robotların değişen ortamlara adapte olabilmelerini imkansız kılmaktadır. Bu tezde, değişen ortamlara adapte olabilen ve insan robot işbirliğini destekleyen bir endüstriyel robot sistemi önerilmektedir. Sistem 4 ana bileşenle gerçeklenmiştir: endüstriyel robot ve konveyör içeren bir tut-bırak işlemi, projeksiyon cihazıyla insan bilgilendirme sistemi, lazer tarayıcı ile algılama sistemi ve kontrol ve haberleşme ekipmanları. Öneri-len sistem gerçekleştirilerek sistemin performansının test edilmesine yönelik deneyler yapılmıştır. Sonuçlar, sistemin tepkisinin endüstride güvenli insan-robot işbirliği için umut verici olduğunu göstermektedir.

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LIST OF SYMBOLS

F_{att}	Attractive potential field force
F_{rep}	Repulsive potential field force
F_{total}	Total potential field force
k	Constant multiplication factor for attractive potential field energy
U_{att}	Attractive potential field energy
U_{rep}	Repulsive potential field energy
U_{total}	Total potential field energy
μ	Constant multiplication factor for repulsive potential field energy
ρ	Euclidean distance between TCP and obstacle
ρ_0	Maximum limit distance of the repulsive potential function

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
APF	Artificial Potential Field
CAD	Computer-Aided Design
COBOT	Collaborative Robot
DOF	Degree of Freedom
HIRC	Human-Industrial Robot Collaboration
HRC	Human-Robot Collaboration
IFR	International Federation of Robotics
IPC	Industrial Personal Computer
ISO	International Organization for Standardization
PTP	Point to Point
ROS	Robot Operating System
RRT	Rapidly-Exploring Random Tree
TCP	Tool Center Point
TCP/IP	Transmission Control Protocol/Internet Protocol

1. INTRODUCTION

1.1. Background

Demands on robotic applications in production lines in industry are increasing rapidly due to their practicality, efficiency and manufacturing quality. According to the report published by International Federation of Robotics (IFR), robot sales increased by more than 30%, and leading areas for this growth are metal, electrical and electronics industry [1]. There are many different types of industrial robots designed for numerous applications such as welding, assembly, material transport, machining and handling. Various studies are carried out around the globe with the intend of increasing the capabilities of industrial robots and robotic production systems. These works range from developing new robot designs with innovative features for establishing advanced software systems on the robots [2–5]. Several studies are also being conducted to make production lines more adaptable to robotic environments [6,7]. One of the main focuses of the studies about improving the current industrial robot technology is human-robot collaboration (HRC). HRC is a popular field of study that aims to pave the way for collaborative processes between humans and robots. This concept is also one of the main concentrations of recent digital revolution in the industry [8].

1.2. Motivation

Even though a production line can be automated with industrial robots substantially, there must still be human operators and workers in the environment to control the robots or collaborate with them, or to carry out other tasks. Unless the necessary precautions are taken, there might be severe consequences concerning human life since the robots perform very quick movements in a large workspace. For that reason, human safety is the top priority while integrating a production line with industrial robots. The most standard method to provide human safety in robotic applications is to put the robot inside of an area enclosed by fences. One example of fenced robotic cell can be seen in Figure 1.1. The fences around the robot form a physical barrier which prevents people from entering the robotic cell. If someone enters the robotic cell, the robot ceases its movement immediately by getting the information from safety sensors around the robot.

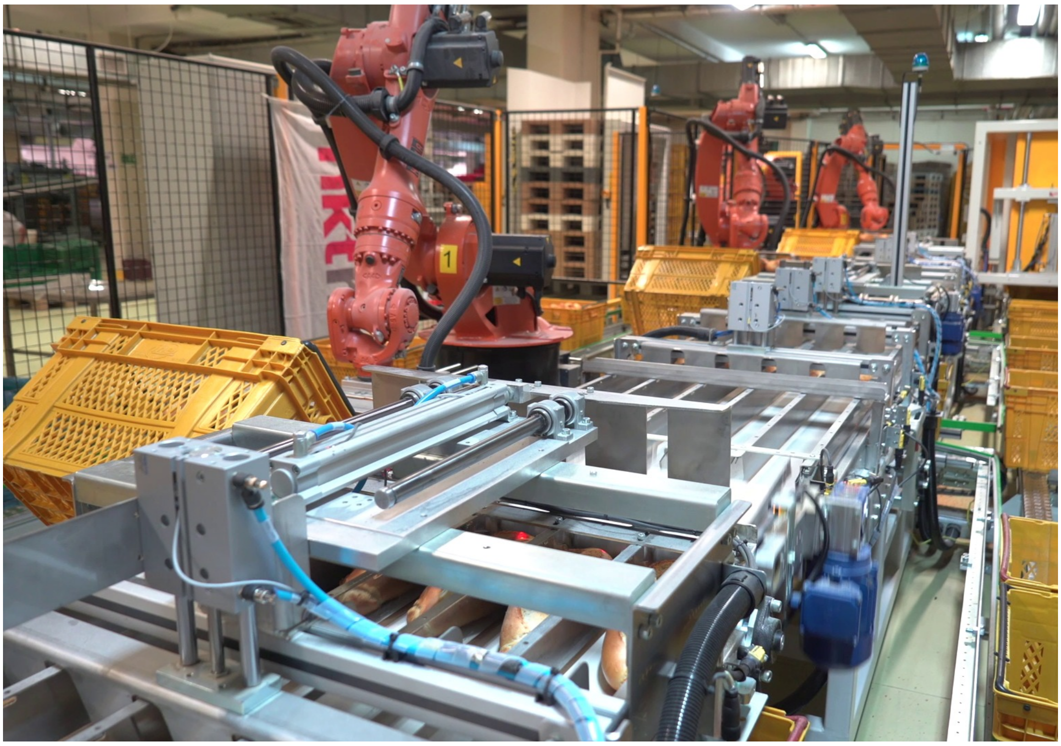

Figure 1.1. A robotic cell with fences.

Although the fences ensure satisfactory safety measures in a robotic production environment, they restrict human-robot collaboration which is considered to be the future of the manufacturing technology [9]. In order to support people in collaborating with robots in industry, and hence to increase the effectiveness of production, new advancements in HRC regarding safety must be carried out.

In 1996, Colgate *et al.* introduced cobots (collaborative robots), which are robots able to work in collaboration with human operators [10]. Afterwards, many industrial robot companies developed their own commercial cobots [11–13]. The main feature of the cobots, which enables them to work with human operators without any physical barrier, is to recognize any unexpected contact through sensors, and stop or alter the motion plan in the presence of such a situation (Figure 1.2).

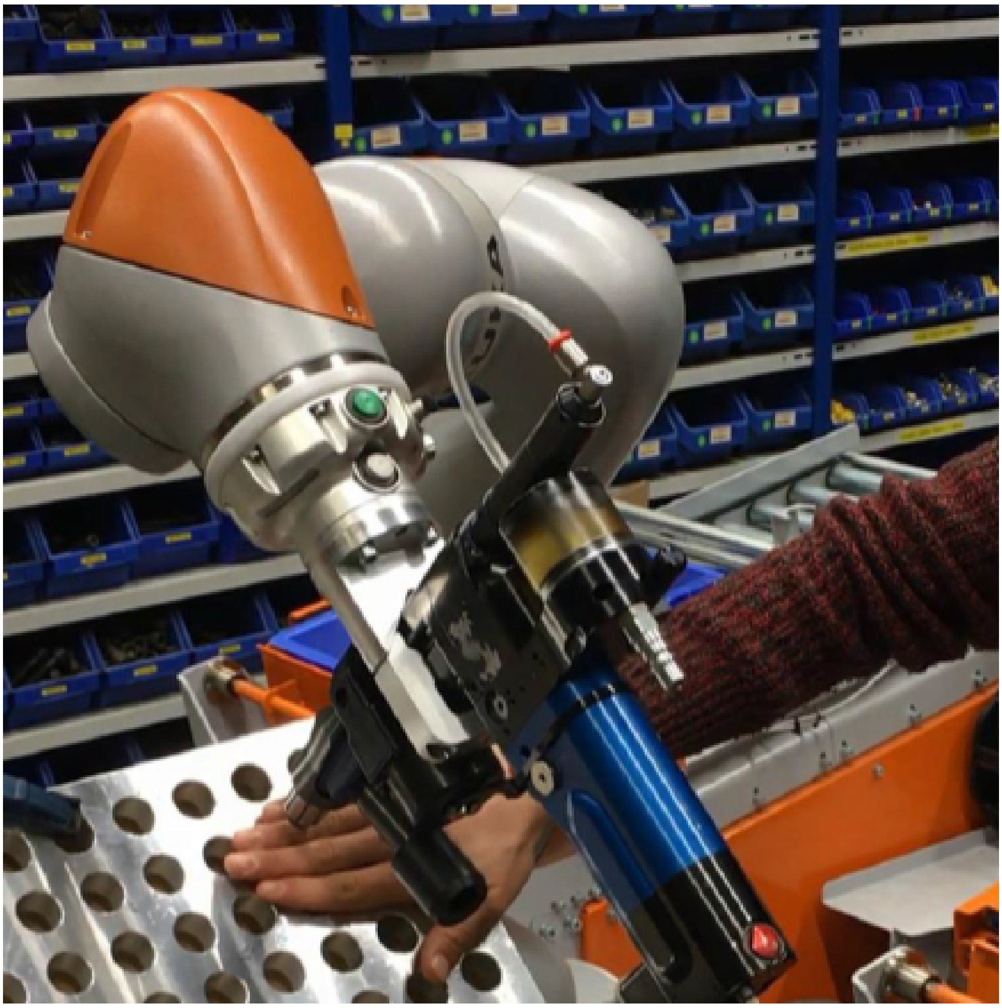

Figure 1.2. A KUKA cobot (LBR iiwa) operating in the existence of a human [14].

Despite the increasing number of cobots in-service, there are still many industrial robots being produced and used without any collaborative properties. In this regard, there are many studies being carried out related to control methods for the industrial robots to provide enhanced production [15–17]. To eliminate the risk of collisions in unorganized working environments with no fences, any path planning algorithm for industrial robots must contain obstacle avoidance properties. There are several obstacle avoidance algorithms proposed in literature and being developed. However, implementation of these algorithms to industrial robots is not actually possible for an end user since these types of robots generally have closed control architectures which makes any changes on control algorithm impossible for the user. The only inputs that are allowed for the user to set in the control algorithm of an industrial robot are generally position references in Cartesian coordinates and joint velocities.

Additionally, unavailability of a dynamic model of the robot restrains any further improvements by the end user. Furthermore, feedbacks obtained from the robot such as current, position, and velocity are very limited. In this thesis, it is hypothesized that conventional industrial robots can be converted into collaborative robots by a novel motion planning technique despite the abovementioned problems. To verify this hypothesis, a path planning algorithm based on conventional programming methods is developed and implemented to an ESTUN ER16 industrial robot in this study.

1.3. Objectives

Aim of this study is to change the existing safety measures of industrial robots, which form a barrier to the human-robot collaboration, by developing a path planning algorithm with obstacle avoidance applicable to industrial robots. Three objectives of this study are as follows:

Objective 1: To develop an enhanced path planning algorithm based on fundamental methods which are already being used in path planning. The main drawback of the existing path planning techniques is that they are not implementable to the industrial robots. We hypothesize that the developed algorithm will be applicable to the industrial robots, and it will improve the collaboration between the robots and humans in industrial applications.

Objective 2: To model the human body as a dynamic obstacle in the workspace of the robot. In order to ensure safety in human-robot collaborative environments, the danger of collision between the robot and human must be eliminated. The developed human model will be the main obstacle in the proposed path planning algorithm.

Objective 3: To implement the developed path planning algorithm to an industrial robot, and carry out validation experiments based on realistic industrial applications with suitable collaborative scenarios.

The objectives are achieved by developing a novel path planning algorithm based on conventional robot programming methods and implementing it to an industrial robot. The system is able to work with humans in close proximity without fences. The main considerations while developing the system are; the developed system should be adequate to be implemented by the robot operators, and the response should be quick enough to eliminate any collision risk. There are three response types of the robot in case of a violation to the workspace: slowdown, avoidance and full stop.

1.4. Thesis Structure

The thesis is organized as follows: Chapter 1 presents the general aspects, motivation and purposes of this study. It also provides a brief overview of the thesis structure. In Chapter 2, literature search carried out throughout this study is shared. Chapter 3 details the developed algorithm and the implementation of the algorithm to an industrial robot. In Chapter 4, responses of the system in each violation scenario are mentioned and discussed. Lastly, conclusions of the research and possible future works are presented in Chapter 5.

2. LITERATURE REVIEW

2.1. Industrial Robots

Since 1980, there has been exponential growth in robot applications in industrial processes such as handling, welding, palletizing, and machine tool loading [18]. An automatically controlled, reprogrammable in three or more axes, multipurpose manipulator which can be either fixed or movable used in industrial applications is called an industrial robot [19]. Industrial robots have begun to replace human workers for the operations mainly taking place in challenging environments as they are able to perform repetitive tasks in an efficient way.

Most industrial robots have six or fewer degrees of freedom (DOF), and they are usually categorized based on the types of the first three joints of the arm [20]. They can be grouped under five types based on their mechanical configurations: Articulated (RRR), spherical (RRP), SCARA (RRP), cylindrical (RPP), or Cartesian (PPP) [20]. Articulated robots (RRR) are one of the most common robots that are used in industry as they can have relatively large freedom of motion in a limited area [20]. They also have high speed, and their design allows for maximum flexibility. Spherical robots (RRP) are (also known as Polar Robots) mainly used for machine tool handling, die casting, welding, and injection molding. SCARA (Selective Compliance Articulated Robot for Assembly) robots are the subclass of cylindrical robots, and they are mainly used for assembly applications in the industry. Cylindrical (RPP) robots play an insignificant role in modern-day's industry due to more convenient alternatives, and preferably used for palletizing, loading, and unloading of machines [21]. Most cartesian (PPP) robots come as gantries, and they are mostly used for handling tasks such as palletizing, warehousing, and order-picking [21].

The articulated robotic arms are the most widely used industrial robotic structures worldwide, covering more than half of annual installations [22]. Also, they are able to operate in higher speeds with higher payloads than the similar machines with six axes [23]. As mentioned, they have large freedom of movement, which means they are able to provide more space and allow for maximum flexibility. For this reason, an articulated robot was chosen to implement the proposed algorithm.

2.2. Human-Robot Collaboration

The increase in robotic manufacturing applications has led to many improvements in factories as it can offer effective performance with accuracy. However, factory areas that require humans and robots to work together have begun to pose some new risks for humans. In order to eliminate these risks, there are several standardizations concerning human safety in industrial robot applications such as ISO 10218:2011 (Robots and Robotic Devices - Safety Requirements for Industrial Robots). The standard emphasizes possible hazards in robotic environments in detail, and offers solutions which must be respected while designing and implementing an industrial robotic system [24]. IFR defines two classes of robots designed for collaborative operations, these are the ones which comply with the International Organization for Standards (ISO) norm mentioned above, and the others that do not meet the requirements [25]. However, the robots that are not in accordance with these standards are not neccessarily unsafe, they may follow different safety regulations [25].

Human-industrial robot collaboration (HIRC) is a field of study that aims to combine the advantages of industrial robots with humans in manufacturing environments [26]. HIRC can include various systems, and can be categorized into different levels of human industrial robot interactions [26]. It can range from a shared workspace without a direct contact to function together in real-time, which means regulating the motion of the robot in order to adjust with the human operator in real-time. Robots that carry out tasks in collaboration with workers in industrial environment are defined as collaborative industrial robots [25]. According to IFR, the most common human industrial robot collaboration is shared workspace applications (Figure 2.1). The highest priority here is to ensure the personnel safety. The proximity between the human and the robot is a critical parameter for apparent security reasons [27]. In the literature, there are several methods to obtain the closest distance between the robot and human depending on the perception method and the robot type. In 2006, Balan *et al.* developed a collision avoidance method including a sphere-based models representing the robot and human [28]. This collision detection method depends only on computing the minimum distance between two sphere which increases computational efficiency (Figure 2.2).

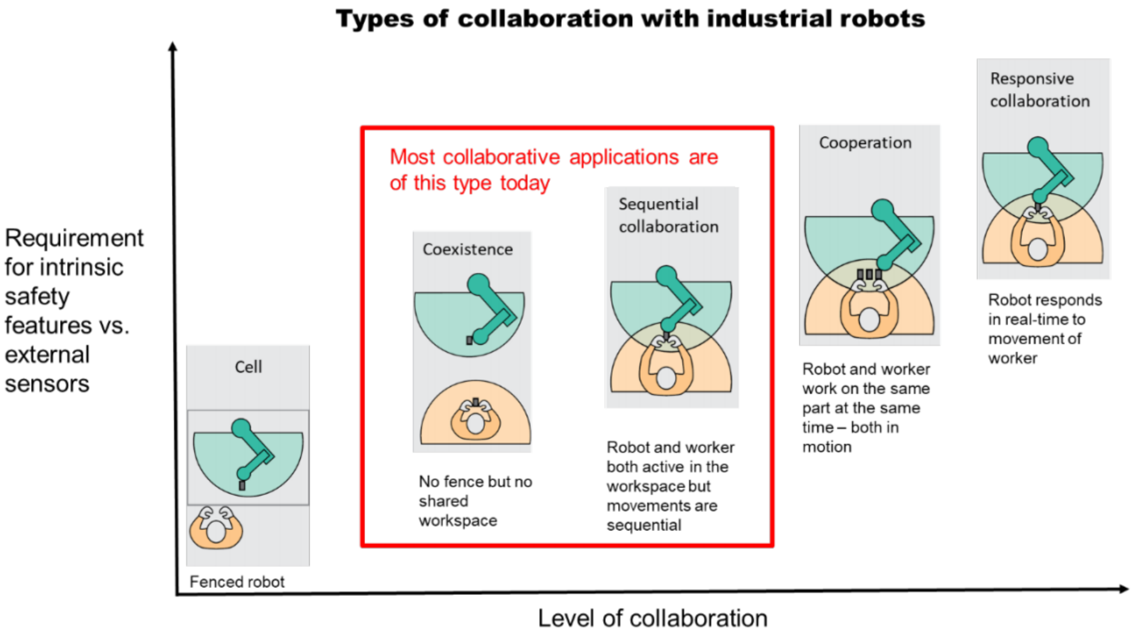

Figure 2.1. Types of human-industrial robot collaboration [1].

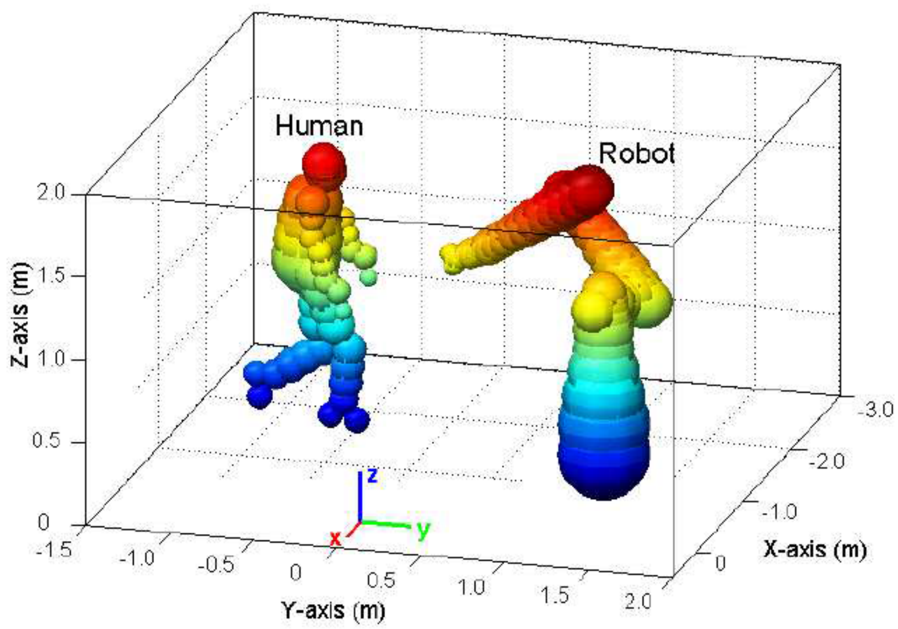

Figure 2.2. Geometric collision detection based on sphere-based models [28].

The most conventional method that is in accordance with the specified standards to ensure the human safety in robotic applications is to surround the robot with fences (Figure 1.1). The fences form a physical barrier which ensures that nobody violates the workspace of the robot. The cage includes one or more gates that allow people to enter the workspace. The sensors on the gates cease the movement of the robot when the gates are opened. Even though these fences ensure safety in such applications, they limit the collaboration and cooperation between humans and robots.

Considering that the future of manufacturing strongly relies on the collaboration between humans and robots, researchers and companies around the globe have started to develop new technologies to remove such physical barriers in robotic workspaces. A method for increasing the safe HRC is building lightweight and compliant mechanical structures. Hirzinger *et al.* focused on lightweight robot to ensure safety in shared workspaces [29], and Ikuta *et al.* mostly focused on the mechanical design [30]. Control based safety strategies are also discussed by them [31, 32]. Adressing the mechanical alterations is not only limited with lightweight robots; a variable impedance approach is also proposed by Bicchi *et al.* [33] which allows the mechanical impedance parameters like stiffness, inertia, and damping to vary during the task. Another method proposed by Haddadin *et al.* [34] and Erden *et al.* [35] is to monitor momentum generalized by the robot to be able to extract more information from a possible physical collision. For ensuring safety in HRC, much attention has been also devoted to sensors, joint torques, and control algorithms. Heinzmann *et al.* [36] proposed a method that limits the torque commands of a position control algorithm. Integration of active and passive approaches to robotic safety for real-time manipulator control has also been proposed. Schiavi *et al.* [37] introduced a method in which the active control detects the position of human and generates motion references while passive control uses joint impedance to ensure safety in the worst-case scenarios.

In order to detect the obstacles inside of the workspace of a robot, many types of sensors can be used. One of the two main types of sensors is proprioceptive sensors and they can be used to measure values within the robot (motor speed, torque, position). Another type is exteroceptive sensors which receive information from the surroundings

[38]. Sensors that might be employed can also be classified as active and passive sensors according to their detection mechanism. Active sensors provide energy to the surroundings and they use the reflected energy to identify the environment whereas passive sensors conceive the data when natural energy is present in the workspace.

2.3. Path Planning Methods

A further step in human industrial robot collaboration is to focus on collision avoidance, detection and reaction capabilities. The paths followed by the robots are generated by algorithms known as path planning algorithms. In general, planning of the articulated manipulators is defined based on the tool center point (TCP) of the end effector with path planning algorithms in order to accomplish a given task. In industrial robot applications, the paths are planned with mainly two programming techniques, which are online path planning and offline path planning [39].

With offline path planning methods, robots follow predefined paths repetitively. In this type of planning, the environment of the robot is perfectly known and the robot is programmed accordingly by robot operators. The main consideration in offline path planning is to be in an optimized time range which highly depends on the programmer's skills and experience. Nevertheless, offline programming algorithms constrain human-robot interaction since the system is not capable of working with changing environments. Online path planning algorithms are able to generate motion plan to the goal on-the-fly. In this case, the robot is informed about any changes in the workspace so that it can plan its motion accordingly. For instance, if a human enters the workspace of the robot, the motion is altered considering the human as an obstacle.

One of the most common online path planning methods while one or more obstacles are present in the workspace is the artificial potential field method (APF). It is an approach in which the goal point is represented as an attractive potential field source and each of the obstacles is modeled as a repulsive potential field source [40]. Superposition of the different potential fields represents the total artificial potential field which is given by,

$$U_{total}(x) = U_{att}(x) + \sum_{i=0}^{n} U_{rep,i}(x) \tag{2.1}$$

where U_{att} is the attractive potential field, U_{rep} is the repulsive potential field, n is the number of obstacles in the workspace of the robot, and x is the coordinates of the TCP. The formulations for attractive and repulsive potential fields can be represented as proposed in [5],

$$U_{att}(x) = \frac{1}{2}k(x - x_d)^2 \tag{2.2}$$

$$U_{rep}(x) = \begin{cases} \frac{1}{2}\mu(\frac{1}{\rho} - \frac{1}{\rho_0})^2 & \rho \leq \rho_0 \\ 0 & \rho > \rho_0 \end{cases} \tag{2.3}$$

where k and μ are constant multiplication factors, ρ is the Euclidean distance between the TCP and the obstacle, ρ_0 is the maximum limit distance of the repulsive potential function.

The forces resulting from the potential functions are,

$$\vec{F}_{total} = \vec{F}_{att} + \vec{F}_{rep} \tag{2.4}$$

where,

$$\vec{F}_{att} = -\nabla U_{att}(x) \tag{2.5}$$

$$\vec{F}_{rep} = -\nabla U_{rep}(x) \tag{2.6}$$

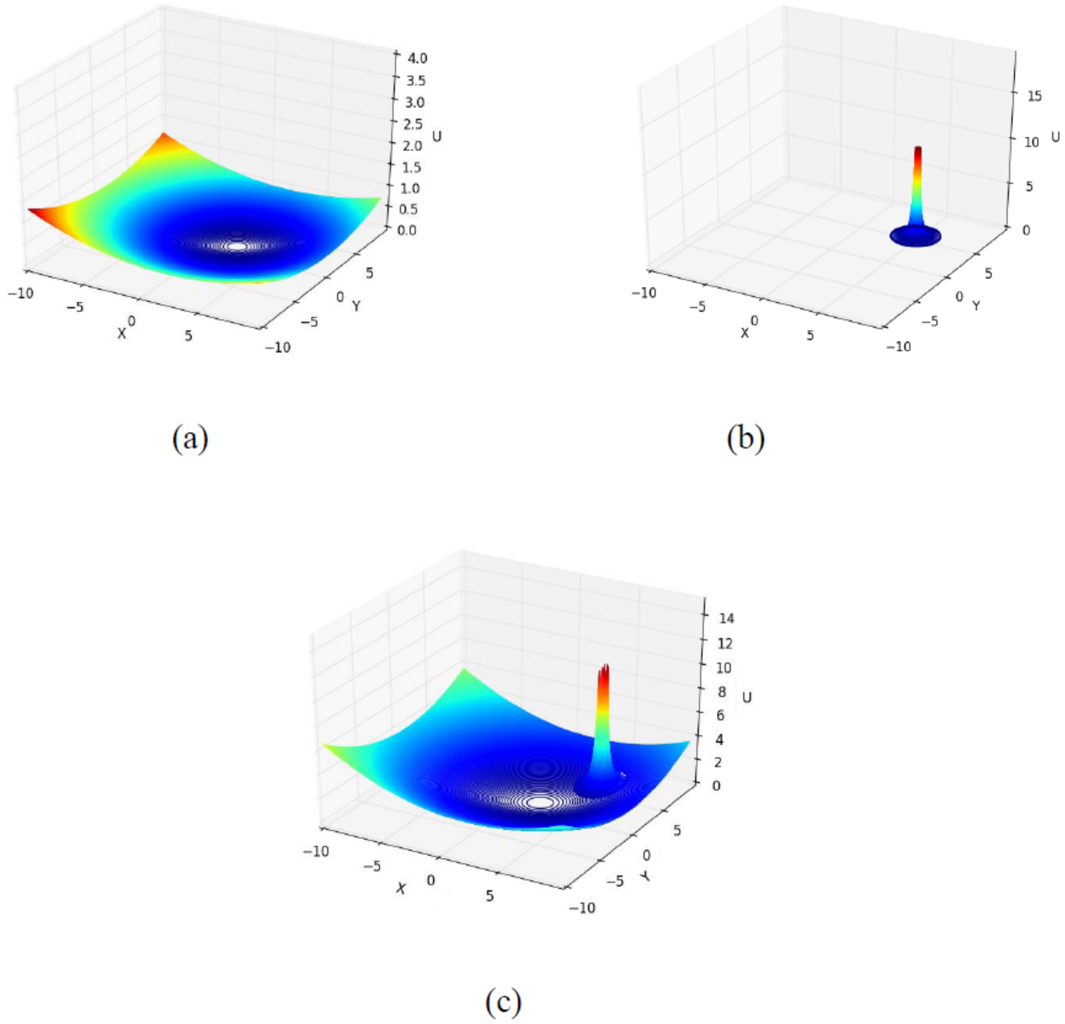

Figure 2.3. Graphical representation of (a) an attractive potential field, (b) a repulsive potential field, and (c) both combined.

In Figure 2.3, a system with a goal point at (-2,-3) and an obstacle at (5, 5) is demonstrated. Repulsive potential energy terminates at infinity at the exact coordinates of the obstacle but it is cut for visualization.

APF method is an effective method to plan a path in an environment involving one or more obstacles. However, it is not entirely applicable to the industrial robots in its present condition mainly due to two reasons: the pre-programmed path planning algorithm in an industrial robot must be completely replaced, and the path for the robot is generated in run-time which makes it impossible to validate before execution [41].

In a study by Pedrocchi *et al.* [41], a novel path planning technique has been developed by combining offline and online path-planning methods using the APF method. Firstly, the offline algorithm models the robot cell using CAD data, and creates "pass-through points" which are points alternative to the nominal path of the robot depending on the static obstacles in the workspace. Then, the online algorithm based on the APF technique chooses the most appropriate points to prevent collisions between the robot and the obstacles and reevaluates the path. In another study [42], an enhanced APF algorithm is presented. Unlike the traditional artificial potential field functions, the algorithm developed in the study uses optimization methods to improve the functions to plan a more satisfactory path.

Along with the recent rapid development of robot technologies, the path planning problem has become a major issue. Many of the conventional methods for path planning are computationally expensive and difficult to realize. However, with sampling-based path planning techniques, a considerable improvement was achieved. Essentially, sampling based algorithms depend on a function that calculates the length between two points in the workspace of the robot [43]. Sampling-based path planning algorithms make use of geometric models to detect the possible collisions. Then the algorithm takes sample points from the free workspace and generates the path to the goal from discrete positions. The outline of the sampling based algorithms can be seen in Figure 2.4.

One of the most used sampling based agorithms is called rapidly exploring random tree (RRT) [44]. In the RRT algorithm, a tree-like structure with nodes initialized from

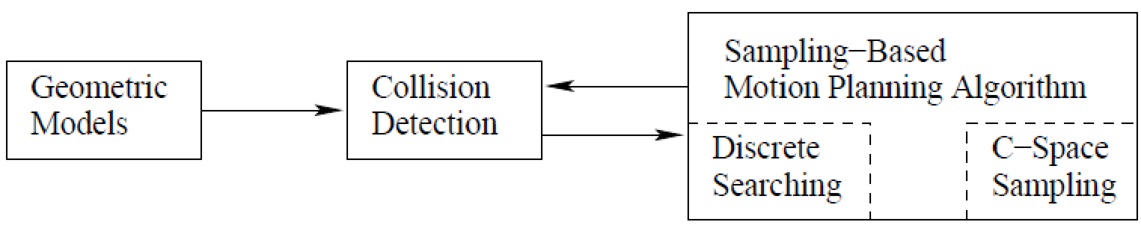

Figure 2.4. Outline of sampling based algorithms [43].

the starting point is constructed based on randomly chosen sample points on the free space. New nodes on the tree are obtained by extending the tree in the same direction with sample point from the closest point at a predefined length (Figure 2.5). Many possible paths are created by combining these nodes. The iteration is stopped when the tree is expanded until it includes the goal point and then the most appropriate path is chosen.

Studies dealing with adapting the sampling based algorithms to the articulated manipulators like industrial robots are also being conducted. In a study by Zhang *et al.* [45], effort and time spent during manual programing of industrial robots is eliminated by implementing an improved RRT algorithm, and the over-searching problem of the RRT algorithms is also avoided by introducing a regression mechanism. In another study, a smoothing approach for the RRT algorithm using a time optimization method of joint trajectories is introduced [46].

One of the most beneficial uses of robotic technologies is in industrial applications where humans are involved to a large extent. Based on the literature search completed throughout this project, it is observed that there are many studies being carried out to increase HRC in industry. However, it can be seen that most of these studies are not dealing with the phase of implementation. The offered solution in this thesis comes up with a novel safe robotic production concept to increase HRC in industry, and a method for implementation.

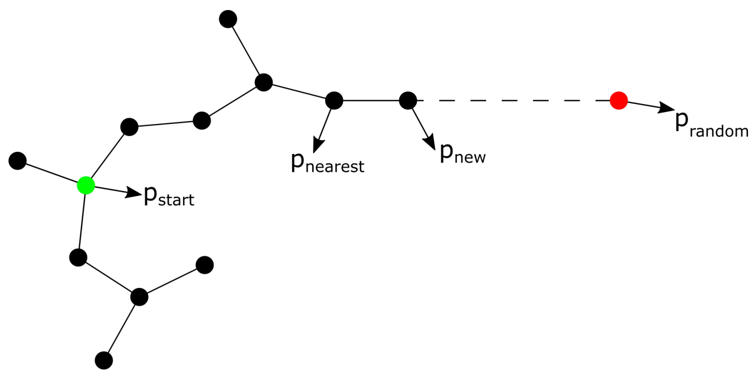

Figure 2.5. The main concept of the RRT algorithm. The black nodes are obtained using the sample points represented in red and they form possible paths to goal point.

3. MATERIALS AND METHODS

The primary objective of this thesis is to increase the human-robot collaboration in industry mainly by developing and implementing a novel path planning algorithm for an industrial robot which is able to update the robot's motion according to position of a human around the robot. In addition to the software alterations to the robot, it is thought that informative features for the operators around the workspace of the robot might also improve human-robot collaboration. Therefore, an information system is also designed and implemented. In the following subchapters, first the overall system is introduced, and then the system components are described in detail.

3.1. Dynamic Obstacle Avoidance System

Every object in the robot's workspace are defined as obstacles. Collision risks between the robot and the obstacles must be definitely avoided since they can lead to severe consequences. Human obstacles should be modeled as dynamic obstacles and the position information should be in real-time in order to avoid any risk of contact due to the unpredictable nature of human movements. In case of a violation, the robot must respond quick enough, and also the altered motion should be safe. The system should be able to work in industrial production conditions, and comply with the related safety standards.

After specifying the design requirements for a collaborative robotic cell, a design including the overall system with the necessary components is established (Figure 3.1). Then, the design is implemented in the production site of HKTM A.Ş. and prepared for the tests.

3.1.1. System Components

- Industrial Pick and Place Scenario with the Robot: In order to test the developed system, an industrial robot is placed in the robotic cell designed in accordance with an industrial pick and place scenario. Packages on a conveyor are picked up by the robot, and they are placed on palletes. If no violation occurs in the workspace, the robot continuosly performs this task.

- Laser Scanning System: The detection of the human around the workspace is accomplished with a laser scanner (SICK microScan3), which is placed in the robotic cell on 30 cm above the ground.
- Path Planning Algorithm: A path planning algorithm is integrated into the controller of the robot. The main feature of the algorithm is that it is able to alter the motion of the robot according to the position data of human obtained from the laser scanner.
- Computer: The calculations are performed on a computer with a robot developing framework called Robot Operating System (ROS) placed near the robotic cell.
- Projection System: Projection system includes a projector and a stage carrying the projector constructed by aluminum sigma profiles.
- Industrial Communication Equipment: Devices to connect all system components to same local network.

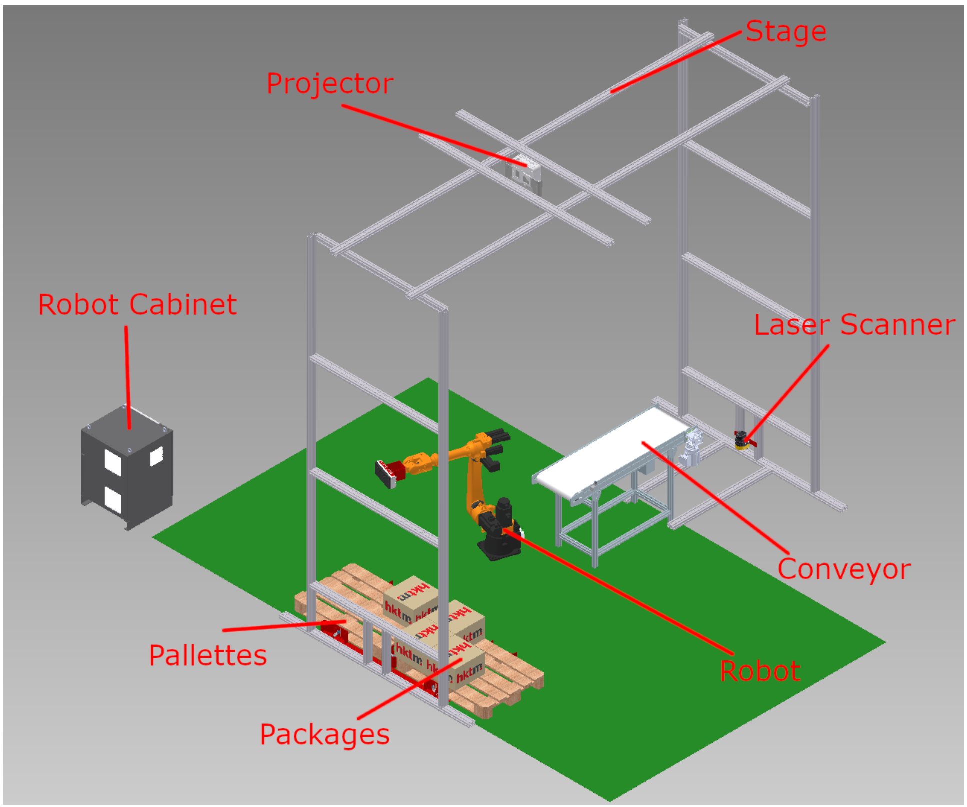

Figure 3.1. Robotic cell design.

3.2. Overview of the Robot

To implement the system for a real industrial application, an industrial robot without any cobot properties was used (Figure 3.2). The ESTUN ER-16 robot manipulator has 6 joints and 6 DOF. The robot can reach up to 1600 mm, and carry up to 16 kg. Repeatability of the robot is 0.1 mm.

The robot is controlled by a KEBA KeMotion controller. Each motor on the robot axes is separately connected to a servo motor driver. The drivers receive signals from the controller and provide precise motion. All drivers, connection components, and the controller are inside the robot cabinet (Figure 3.3).

Figure 3.2. ESTUN ER16 industrial robot is used to implement the developed system. The robot is a six-axis articulated manipulator.

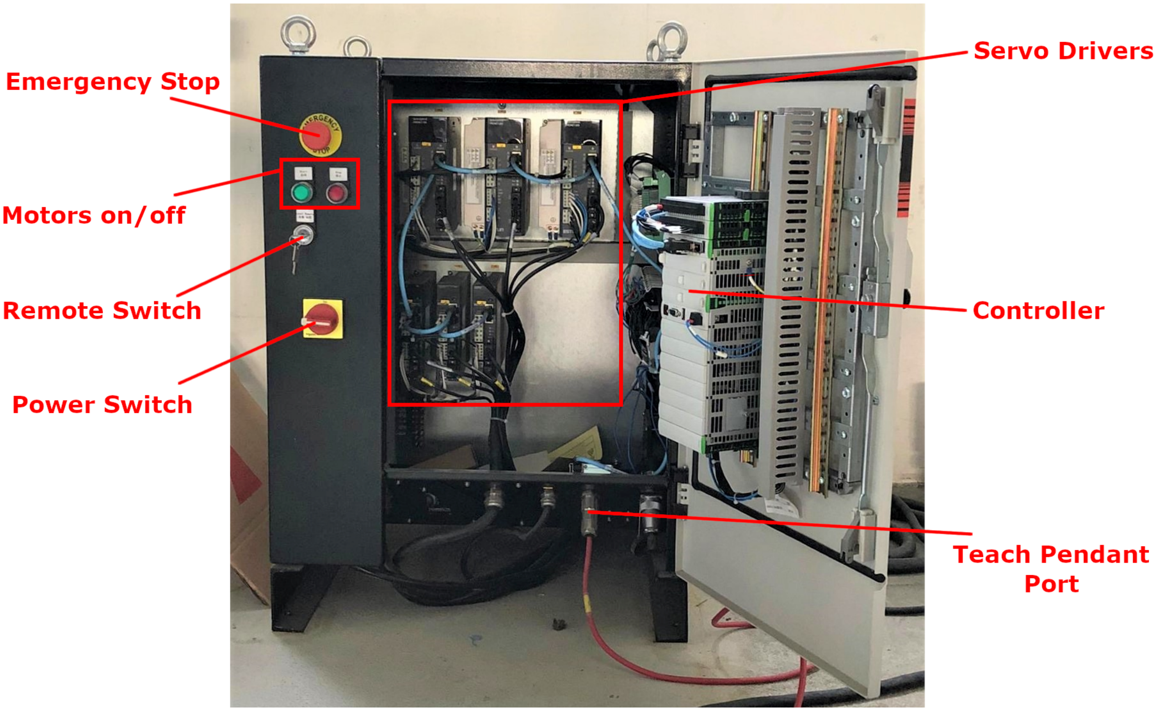

Figure 3.3. ESTUN ER16 robot cabinet.

3.2.1. Industrial Robot Programming

The robot controller is programmed with KEBA KeTop T70 teach pendant using KAIRO robot programming language. KAIRO is designed for robot operators to implement user programs. The language has been built simple to make programming operations easy for the operators without requiring advanced programming skills. KAIRO includes many sets of movement commands, settings, and system functions, and supports 16 basic data types with no necessity of declaration. Operators generally define the movement of the robot in the code by the following main movement commands:

- PTP: Point to point movement command.
- Lin: Linear movement command.
- Circ: Circular movement command.
- MoveRobotAxis: One robot axis movement command.
- StopRobot: Stopping command.

Table 3.1. Parameters of the basic movement command PTP in KAIRO robot programming language.

Parameter	**Explanation**
targetPos	Target position
[dyn]	Dynamics data
[ovl]	Overlapping data

Parameters defining positions, dynamics data and overlapping data are entered under these movement commands, and a motion plan following user-defined positions is automatically calculated by a built-in path planner on the robot controller (Table 3.1). Target position defines the goal point, dynamics data defines the speed, acceleration and jerk values, and overlapping data defines the curvature around a target point to have continuous and smooth motion. However, reevaluating the motion plan of the robot in a changing environment is not possible with these commands since they are designed to stop only in case of an emergency input from a sensor or a user input from the teach pendant. To overcome this problem, the following movement command options and instructions of KAIRO are used to develop the novel path planning algorithm:

- PTPSearch: Point to point movement command with a trigger feature.
- LinSearch: Linear movement command with a trigger feature.
- GOTO: Jumping different parts of the program.

Jumping target for GOTO function must be defined with a LABEL instruction. This instruction is used in the developed algorithm to make the function work in a loop. The PTPSearch and LinSearch motion commands take more parameters than the previously mentioned commands (Table 3.2). These extra parameters such as triggerSignal (in BOOL data type) enable the possibility to intercept and replan the motion. For instance, when a trigger signal parameter is specified on a PTPSearch command, and the trigger is set to RISINGEDGE (trigger is on hold when FALSE, activates when it becomes TRUE), the robot stops the movement and robot program

Table 3.2. Parameters for the movement commands with a trigger feature.

Parameter	**Explanation**
targetPos	Target position
triggerSignal	Digital trigger signal
[dyn]	Dynamics data
[trigger]	Rising or a falling edge on the trigger signal
[triggeredPos]	Robot position when the trigger signal is received
[stopRobot]	Stop robot after trigger signal
[stopMode]	Method for stopping

passes to the next line when the trigger signal becomes TRUE. FALLINGEDGE is the valid option for the reverse operation.

3.2.2. Communication Through ROS and Sockets

The software system dealing with data processing and communication in this study is developed using Robot Operating System (ROS). ROS is an open-source framework specialized in controlling robots. ROS provides many libraries and tools to create robot applications making it a universal standard among robot developers in academia. In order to adapt ROS to industrial applications, an extension called ROS-Industrial is also being developed. The main purpose of ROS-Industrial is to offer a common platform for industrial robots from different manufacturers, and related components such as sensors, grippers and controllers. Even though ROS-Industrial support is increasing day by day by providing interfaces to many different industrial robots, ESTUN ER16 is not supported currently. For that reason, a communication protocol in ROS has been developed for ESTUN ER16 and shared in this study.

ESTUN ER16 controller supports Modbus TCP/IP and TCP/IP industrial communication protocols. It may also support PROFIBUS by adding corresponding hardware modules. In this study, the protocol is chosen as TCP/IP since the communication with the robot can be performed with socket programming through ethernet.

Socket programming is a way to share continuous data streams between different devices connected to the same network. The most typical usage of socket programming applications is client-server based, where one device in the network acts as a server and others act as clients. In this project, the robot controller, a ROS computer, and the laser scanner are connected to a local network using Ethernet ports and industrial communication equipment. The equipment involves an Ethernet switch to put all devices in the same network, terminal block for wiring, a power supply, and a circuit breaker (Figure 3.4). Each device in the network is assigned to different IP addresses, and the corresponding ports are assigned accordingly. The ROS computer is chosen and built as the server, and the other devices act as the clients.

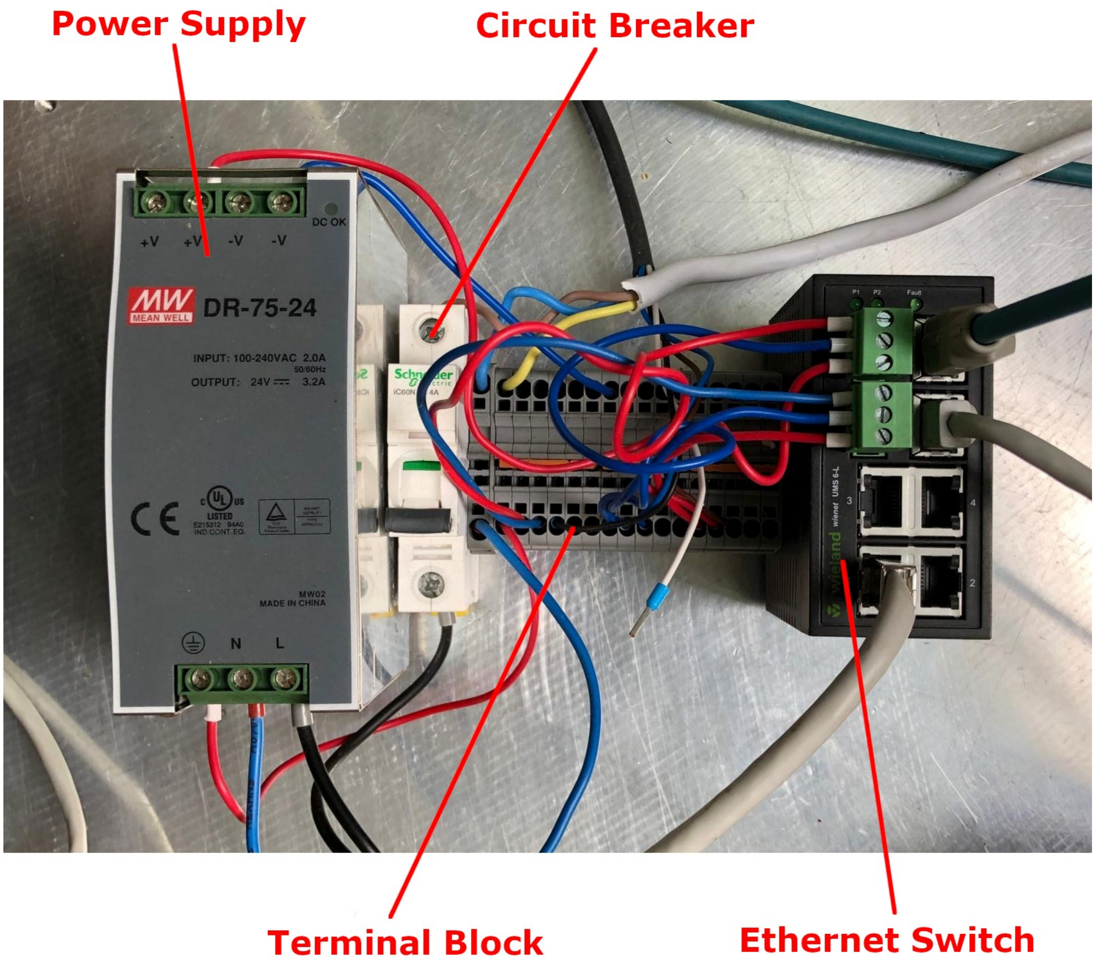

Figure 3.4. Equipment used for adding all devices to the same network.

Table 3.3. Robot variables received and sent through TCP/IP socket streams. The names of the variables are assigned according to their order.

I/O	Variable Type	Variable Number
I	INTEGER	20
I	REAL	20
I	BOOL	32
O	INTEGER	20
O	REAL	20
O	BOOL	32

Support for TCP/IP socket communication of the robot is activated by adding six types of input and output variables to the robot controller. The types of the variables and the numbers for each type can be seen in Table 3.3. These variables can also be checked from the variable list in the teach pendant of the robot (Figure 3.5).

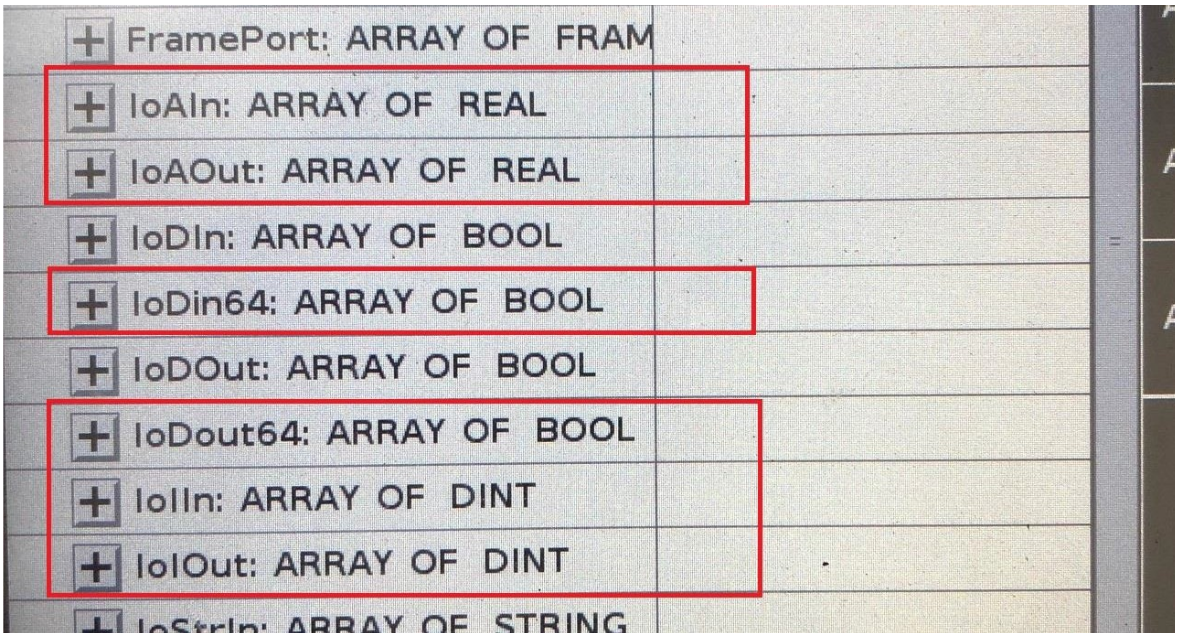

Figure 3.5. Robot variables on teach pendant.

```
import socket
TCP_IP = "192.168.100.66"
TCP_PORT = 3000
BUFFER_SIZE = 512
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.bind((TCP_IP, TCP_PORT))
while True:
    s.send(data1)
    data2 = s.recv(BUFFER_SIZE)
```

Figure 3.6. Socket communication script written in Python.

In the ROS computer, the socket programming library of Python is used to communicate with the other devices in the network. Figure 3.6 illustrates a basic Python script for sending and receiving data using socket programming. IP address, port number and buffer size are specified in the script. After the establishment of the connection, data transfer is accomplished in an infinite loop. The script can be easily integrated in any ROS node written in Python.

3.3. Human Detection

The industrial robots are generally isolated from humans due to potential safety risks. This separation presents limitations for HRC in industry. The robotic cell proposed in this thesis aims to eliminate this isolation. For this purpose, a system that detects the humans entering to the robotic cell is presented so that the robot updates its motion according to the position of the human.

3.3.1. Leg Detection with a Laser Scanner

In order to detect and track the position of persons violating the workspace, a SICK microScan3 safety laser scanner is used. The specifications of the laser scanner are shared in Table 3.4. The laser scanner is placed 30 cm above the ground as seen in Figure 3.7. The laser scanner works only in 2D. The laser scanner data is sent to

Table 3.4. Specifications of the SICK microscan3 laser scanner.

Protection Field Range	5.5 m
Warning Field Range	40 m
Scanning Angle	275°
Angular Resolution	0.39°
Scan Cycle Time	30 or 40 ms

the ROS computer in real-time via the sockets. All 2D data obtained from the laser scanner is processed by the computer with a leg tracker algorithm in ROS [47]. The algorithm detects the legs from the scanned 2D point clusters, and obtains the real-time position of humans. The algorithm is able to detect more than one person at the same time. The performance of the algorithm is enhanced by filtering the 2D scanning data using the plug-ins in the "laser_filters" package of ROS.

If an object is detected by the laser scanner, the back side of the object becomes undetectable. Therefore, in that case, it is assumed that there are no undetected objects behind the leg.

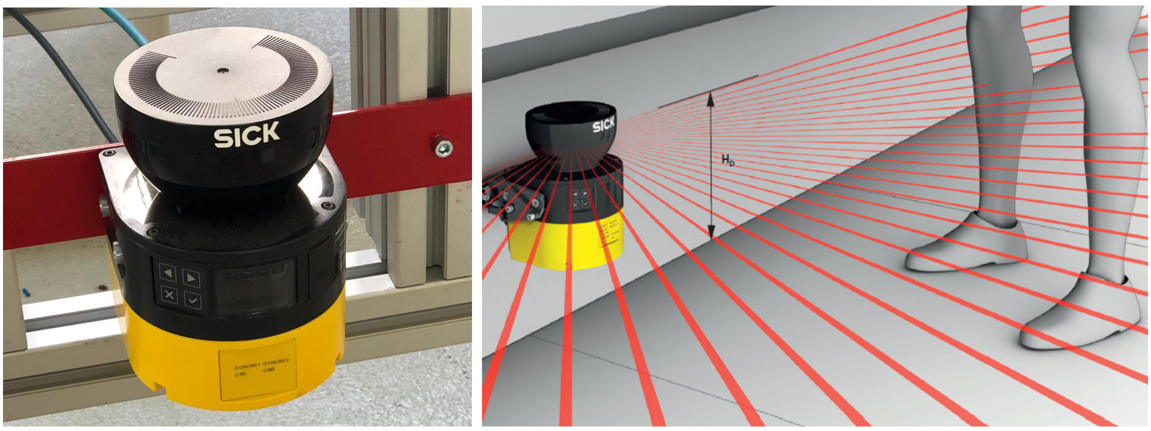

Figure 3.7. The laser scanner placed in the workspace (left), and the leg detection concept with the laser scanner (right) [48].

3.3.2. Proximity Calculation

To update the motion of the robot according to any violation of the workspace, the distance between the human obstacle and the robot should be calculated. The position of the human is obtained in 2D (X and Y in this case) by the scanner. X, Y and Z axes of the robot can be seen in Figure 3.8. The real time position of the robot's Tool Center Point (TCP) is also obtained from the robot's controller. Since no path will be generated by the robot above the detected human, the distance calculations are held on 2D (XY plane) and Z position of the end effector is neglected. However, calculating the distance between the human and the TCP is not convenient enough since there is a possibility that the human in the workspace might be closer to the other parts of the robot even though they are far from the TCP. In order to avoid this problem, and reduce the computational cost, whole robot body is represented with 6 points in 2D. These 6 points are placed consecutively between the fixed base and the TCP of the robot, and they change in real time according to the position of the TCP and robot axes. The described distance calculation method and robot representation points can be seen in Figure 3.9. In this case, diameters of the circles are set to 1 m. When the distance between the human and the robot is below 2 m, at least one of the circles representing the robot and the circle representing the human intersect with each other. The minimum distance is calculated between the robot representation points and the human, and it indicates the instantaneous closest proximity between the robot and the human. The robot alters its movement states described in Section 3.4 according to this measurement.

3.4. Path Planning Algorithm

According to the position of the human in the workspace, the robot has four movement states:

(i) Regular Movement: No threat is detected by the sensor in this scenario. The robot performs the pre-planned motion.
(ii) Slowdown: A threat is detected by the sensor, but there is a safe distance between

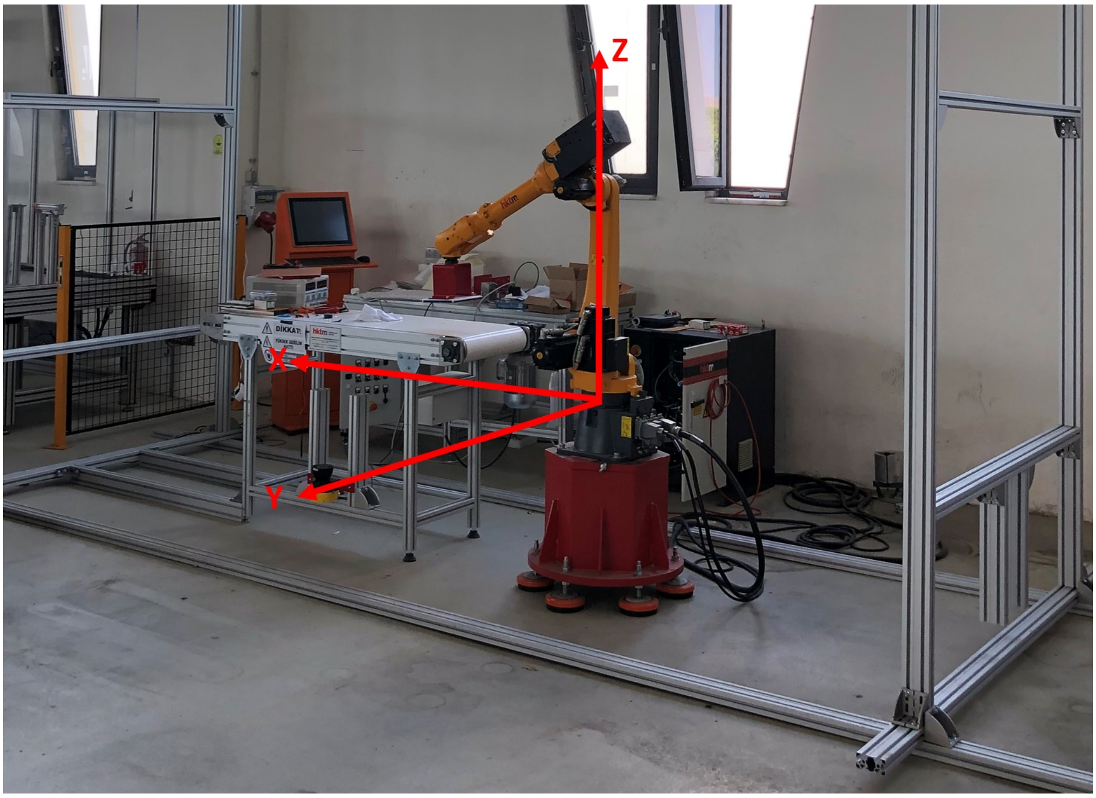

Figure 3.8. X, Y, and Z axes of the robot.

the threat's position and the robot's path. The robot continues to perform the same pre-planned motion at a lower speed.

(iii) Avoidance: A threat is detected by the sensor, and it is likely that it will collide with the robot. Safe distance between the threat and the robot can be restored by taking the robot to a different position.

(iv) Full Stop: A threat is detected by the sensor, and it is in an unavoidable position, so that the robot is stopped.

As it is stated in Section 3.1, the existing motion commands in the robot controller are not open to intervention using the variables defined in the robot. They are mostly adjusted to plan the motion offline. Therefore, a new motion command function that updates the motion of the robot according to the states stated above has been developed for the robot controller. The function is called "ptp_safe". It can be programmed with the same steps as the ones used for the basic motion commands by robot operators with the parameters in Table 3.5. The main feature of the "ptp_safe" path planning

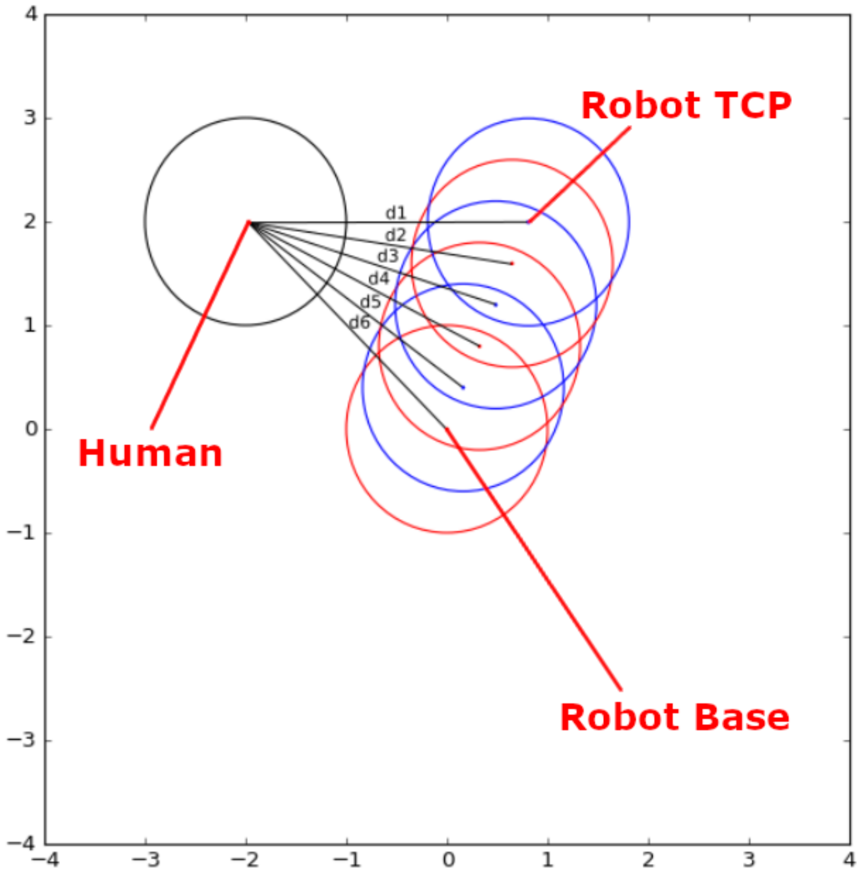

Figure 3.9. 2D projections of the robot and human obstacle. Human is represented with one point while the robot is represented with six points. The circles are drawn for visualization purpose.

function is that it includes an algorithm that updates the motion of the robot according to the motion states depending on the human position. The algorithm requires two critical variables which are named as INTSIG and TRIGGERSIG. TRIGGERSIG is in BOOL type, and it is used as the trigger command. INTSIG is in INTEGER type, and it determines the motion state (Figure 3.10). The stopping scenario is accomplished with setting the TRIGGERSIG to TRUE. Other motion states regular movement, slowdown, and avoidance are accomplished by setting their values to 0, 1, and 2. These variables are constantly updated in the ROS computer according to the position of the detected human and it is continuously streamed to the robot with the TCP/IP socket communication.

Table 3.5. Parameters for the “ptp_safe” function.

Parameter	**Explanation**
GOAL_POSE	Target position
TRIG_SIG	Digital trigger signal
GETAWAY_POSE	Avoidance point
INT_CHECK	Digital motion state signal

The avoidance points mentioned in Figure 3.10 are named as GETAWAY_POSE points in the “ptp_safe” function. The GETAWAY_POSE points are predefined points on a circle around the robot base. It is ensured beforehand that the robot reaches these points without any problem. When the robot is in avoidance scenario, it sets the closest GETAWAY_POSE point as the goal point and starts to move towards that direction. The avoidance movement is ceased at the time when the safe distance is restored even though it did not achieve the get-away point goal.

3.5. Projection Based Operator Information System

The main component of the designed information system is a projector which projects the safe and unsafe zones to the ground of the robotic cell. Any human getting closer to the robot is able to see the informative signs. A conceptual design of the projection system design can be seen in Figure 3.11.

The projected image includes four safety zones drawn in green, yellow, orange and red changing in real time according to the movement of the robot and the position of the human. Each zone represents the situation where the robot will change its movement states according the the position of human. The real-time TCP position data and the human position data obtained through the sockets are used to generate the dynamic image.

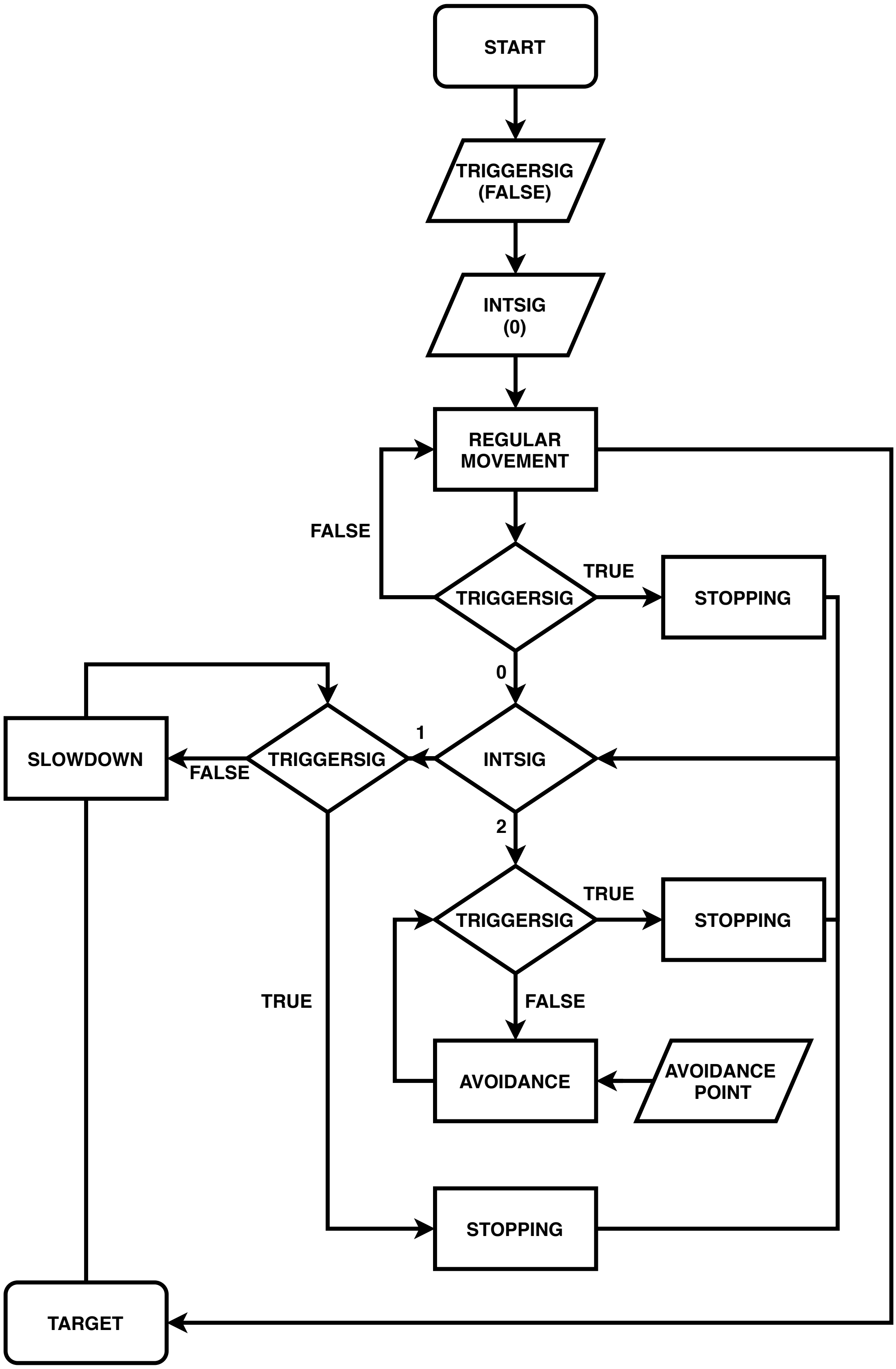

Figure 3.10. Path planning algorithm flowchart.

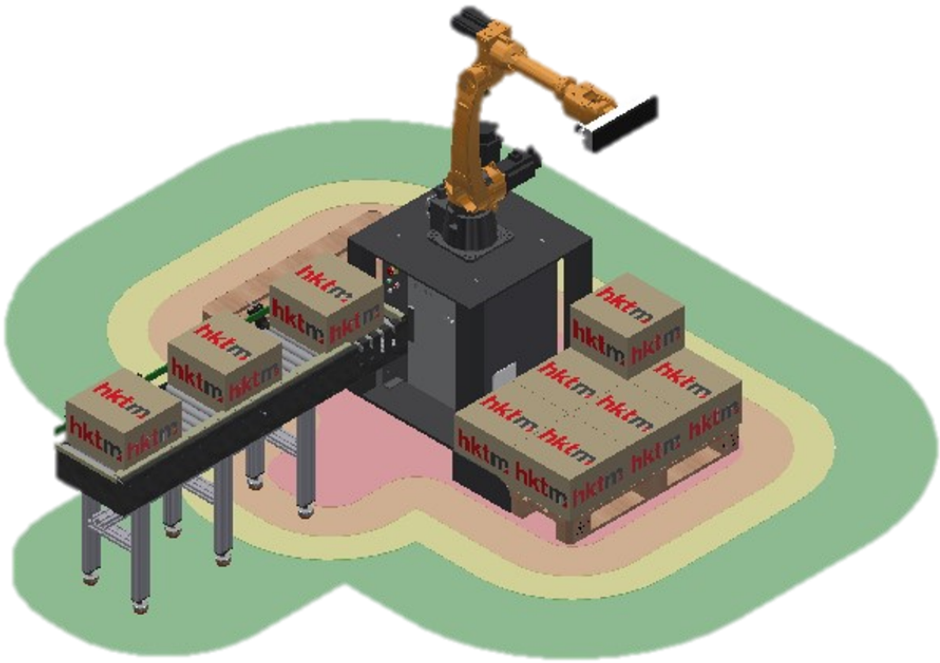

Figure 3.11. Conceptual design of the projection based operator information system.

3.6. Experimental Methods

The designed robotic cell has been implemented in the production site of HKTM A.Ş., and validation experiments were carried out with this prototype (Figures 3.12, 3.13). The conveyor, the laser scanner, and the projector are fixed to the aluminum stage built for the experiments. Due to lack of enough space in the production site, one side of the robotic cell is allocated for the cabinet and other equipment. Human-robot tests were performed on the free side of the robot. The laser scanner is placed to detect the humans in the free side of the robot.

Tests were completed separately for each of the following three reaction scenarios: slowdown, avoidance and full stop. The robot's predefined motion is interrupted when the minimal distance between the human and the robot is below 2 m. For the tests, the robot is programmed with the developed path planning function on the teach pendant to perform an arc-type predefined periodic motion between points (0.523, 0.686) and (-0.882, 0.063). Z-axis stays the same. The position of the TCP in X and Y axes changing periodically through the time can be observed in Figure 3.14.

Figure 3.12. The robotic cell with all necessary components implemented in the HKTM A.Ş. production site.

3.6.1. Slowdown Tests

Slowdown is the first response of the robot in case of human violation of the workspace. In this experiment, a human entered the workspace of the robot, got lower than 2 m close to the robot, and then stopped. The human is detected by the sensor as a threat, but there is a relatively safe distance between the threat's location and the robot's position. The robot is expected to continue to perform the predefined motion commands at a lower speed. As long as the threat is in this area, the robot should move in this scenario.

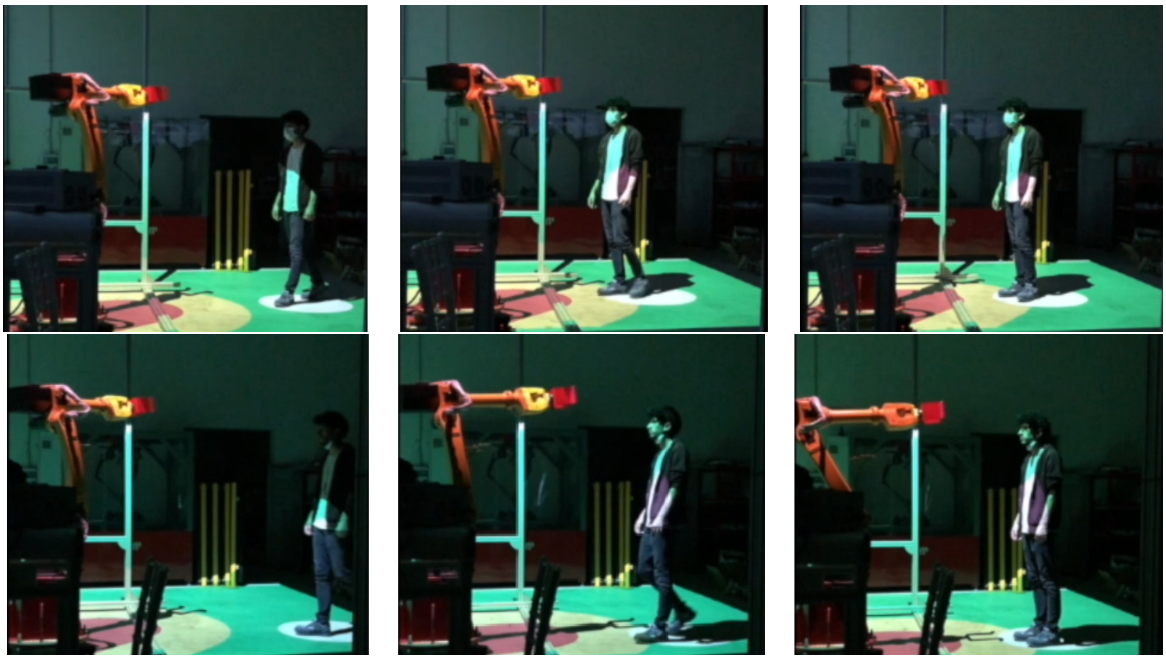

Figure 3.13. Experiments conducted in the production site with ESTUN ER16 industrial robot, laser scanner and the projector.

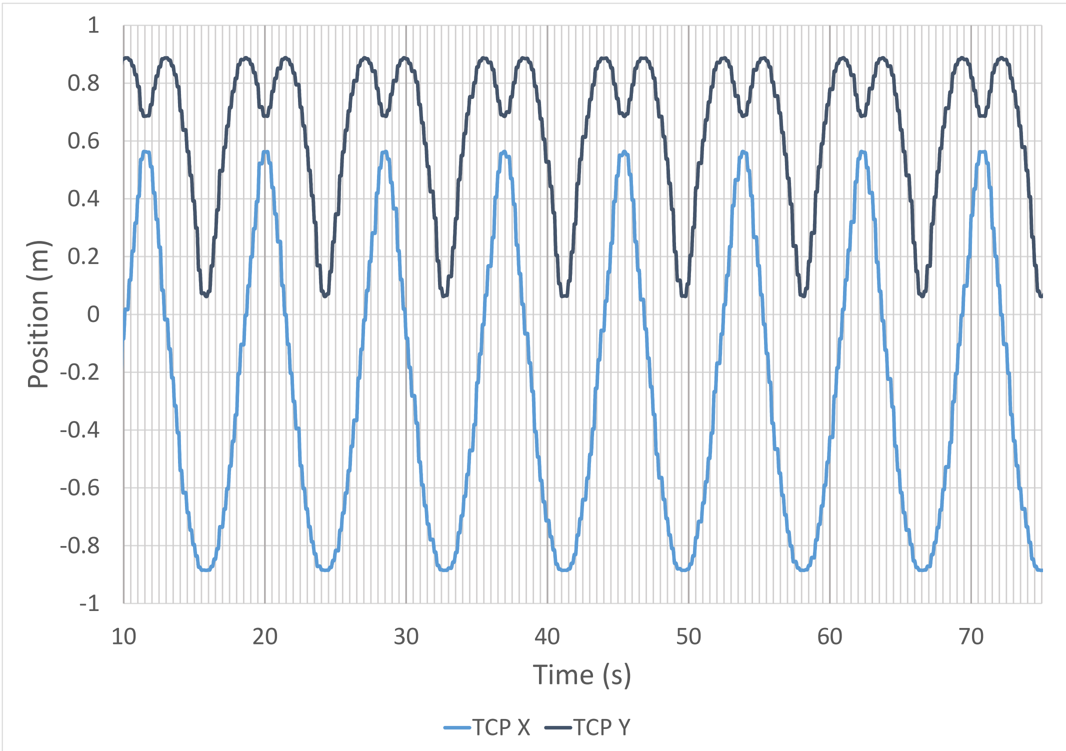

Figure 3.14. TCP position in X and Y axes while the robot performs the predefined motion.

3.6.2. Avoidance Tests

In this scenario, the probability of collision between the threat perceived by the sensor and the trajectory of the robot was emerged. Safe distance between the human and the robot is expected to be restored by taking the robot to an appropriate predefined get-away position. During the experiments, a human entered the workspace of the robot and violates the safe distance limits which is set as 2 m and then stopped. Then the robot's reaction was observed. After the safe distance was achieved, the movement of the robot is expected to be updated according to the algorithm illustrated in Figure 3.10.

3.6.3. Full Stop Tests

This situation indicates that the human detected by the sensor is in an unavoidable position and the robot should be stopped. The robot's periodical motion is planned to be ceased immediately when the minimum distance between the robot and human is below the predefined threshold value. The robot is planned to continue its regular movement when the thread leaves the workspace. During these tests, a human entered the workspace of the robot, got lower than 2 m close to the robot, stopped, and then left the workspace. The response of the robot in this scenario was observed during the experiment.

4. RESULTS

Results of the experiments conducted in the developed safe robotic system are shared in this chapter. According to the obtained results, the performance of the system is also explained and presented with graphics.

4.1. Slowdown Results

Reaction of the robot in case of human violation during the slowdown scenario can be seen in Figure 4.1. The orange line indicates the minimum distance between the human and the robot which is calculated in real-time with the method described in Section 3.3. The green horizontal straight line indicates the threshold distance value between the human and the robot which was set to 2 m for the experiment. The blue line indicates position of the TCP at that time in the specified axis.

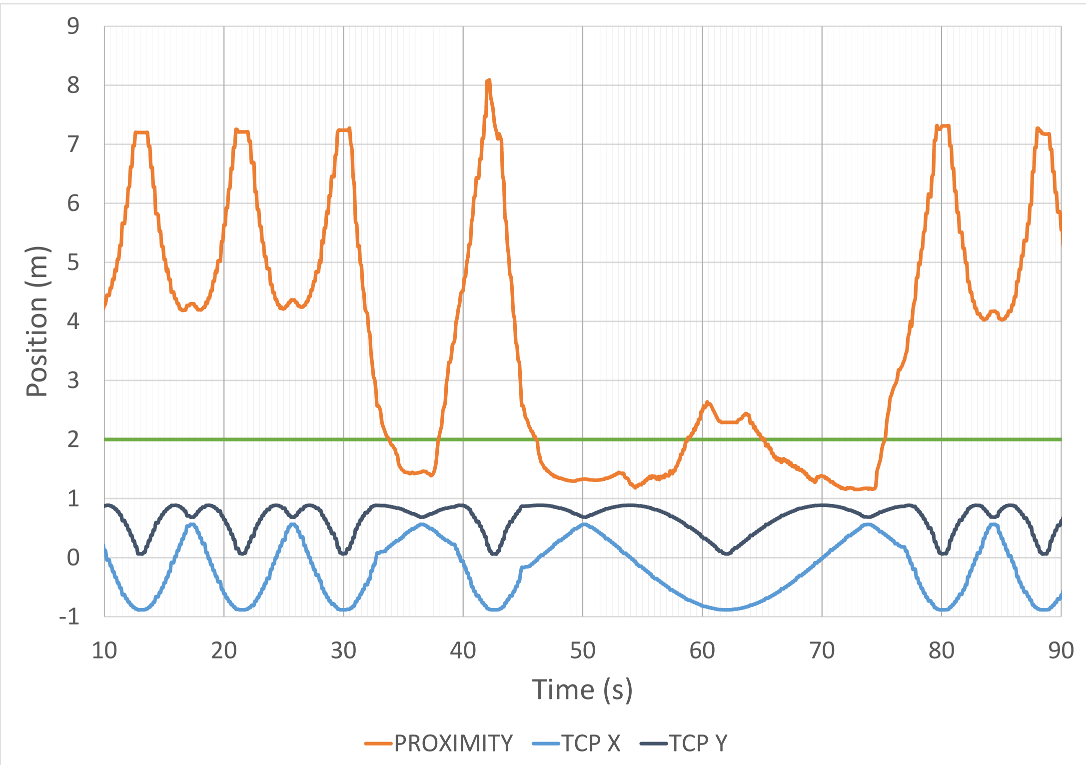

Figure 4.1. Slowdown results in X and Y axes. PROXIMITY is the minimum distance between the robot and the human. TCP X and TCP Y are the position of the robot.

When the calculated minimum distance was below 2 m (respectively measured between 33rd and 37th, 46th and 58th, and 65th and 75th seconds), the robot performed its predefined motion at 1/3 of its initial speed as intended. When the human left the workspace, the safe distance was restored, and the robot started to move in its normal speed.

4.2. Avoidance Results

Figures 4.2 and 4.3 demonstrate the avoidance performance of the system during two experiments with the identical procedures. The lines with the same color indicate the same values as it is stated in Section 4.1.1. As expected, when the minimum distance between human and the robot got lower than 2 m, the robot immediately started to reestablish the safe distance. After the safe distance was restored, the robot started to move to the goal point. The maximum exceeded distance is measured as 0.3 m during this motion.

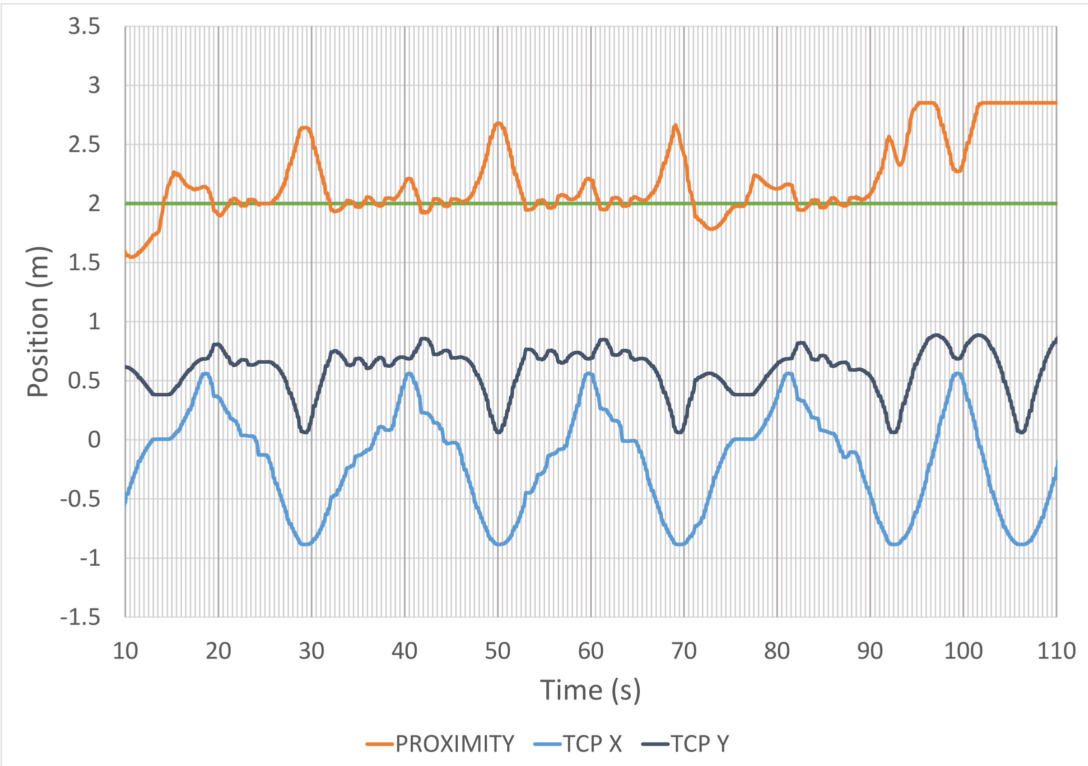

Figure 4.2. Avoidance experiment one. PROXIMITY is the minimum distance between the robot and the human. TCP X and TCP Y are the position of the robot.

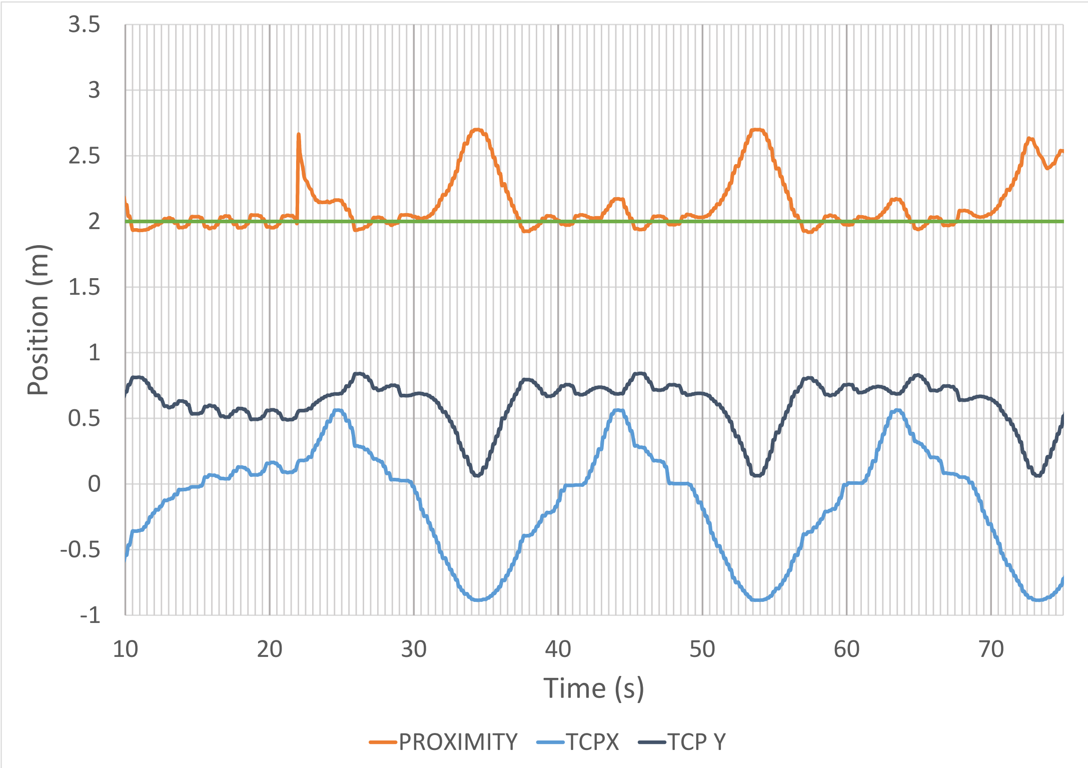

Figure 4.3. Avoidance experiment two. PROXIMITY is the minimum distance between the robot and the human. TCP X and TCP Y are the position of the robot.

4.3. Full Stop Results

Full stop performance of the system can be seen in Figure 4.4. The lines with the same color indicate the same values as it is stated in Section 4.1.1. The robot ceased its movement when the its closest proximity to the human is under 2 m. The response time of the robot was measured as 0.3 s from the data obtained in the experiment. After the safe distance was restored when the human left the workspace, robot continued to perform its regular movement.

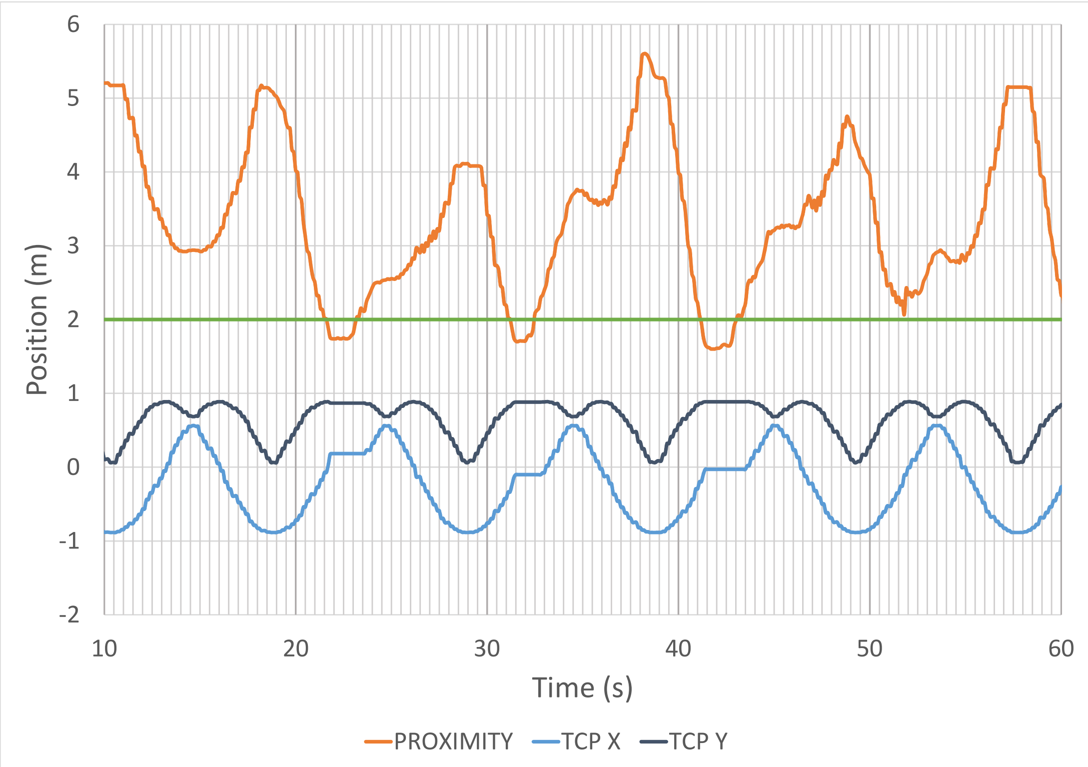

Figure 4.4. Full stop experiment. PROXIMITY is the minimum distance between the robot and the human. TCP X and TCP Y are the position of the robot.

5. DISCUSSION AND CONCLUSION

In most cases, industrial robots are built in an area enclosed by fences to ensure safety in a production environment. However, manufacturing processes are tending towards applications involving humans and robots working in the same environment with the aim of increasing efficiency. Conventional industrial robotic systems do not allow interaction between humans and robots in close range since they can perform very rapid movements in a short time interval which may lead to serious injuries.

In this thesis, a path planning algorithm including obstacle avoidance has been developed and integrated to the controller of an industrial robot. A laser scanner was used to gather position information of human obstacles. In addition, a projection-based warning and information system has been developed in order to increase the safety in human-robot collaboration in industry. The overall system has been integrated into a robotic cell. Safety zones are projected on the robot floor with this setup.

Several experiments were performed to test the performance of the system in slowdown, avoidance and full stop scenarios. During the experiments, the robot was programmed with the developed algorithm to perform a pre-planned motion. If no violation occurs in the workspace, the robot continues its regular movement as it is programmed offline. In case of a human violation, robot takes three actions according to the minimal distance: slowdown, avoidance and full stop. Reaction and response time of the robot under these situations were analyzed in accordance with the robot's position data and proximity to the human obtained through TCP/IP socket communication. Robot is able to change its motion depending on the previously mentioned safety scenarios, which indicates that the system is shown to be promising for safe HRC in industry.

5.1. Contributions and Originality

The originality of this study is achieved by developing and implementing the path planning algorithm in the already existing closed control system of an industrial robot. The algorithm is presented as an easily implementable conventional movement function for the robot operators.

Another novelty of the system is that it brings out collaborative properties for the commonly used conventional industrial robots supporting HRC which is considered one of the key properties of the digital industrial revolution.

5.2. Outlook and Future Work

The developed system paves the way for controlling industrial robots without any specialized interfaces by proposing an implementation method based on TCP/IP socket communication. Other algorithms can be applied to different types of robots using this technique.

The proposed industrial robot system is a promising study for human-robot collaboration in industry, yet there are several points that should be taken into account in future usages. Firstly, during the experiments, the industrial robot was placed in a pick and place operation. However, other operations such as assembling and machining may require different components (even an additional robot). The system should also become adaptable for this kind of different scenarios. Secondly, due to the unpredictable nature of human movements, the obstacle modelling for the human body must be accomplished meticulously. In this study, humans in the workspace of the robots are modeled as dynamic obstacles and their positions are obtained through a laser scanner. Even though the laser scanner gives satisfactory solutions, the detection sensitivity and response time can be improved by other sensors such as RGB-D cameras. Shadowing the back of the object is an issue of the laser scanners, and it may also be eliminated by adding new sensors. Lastly, the experiments can be improved by testing all the motion states working consecutively with more than one human around the robot.

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APPENDIX A: DATASHEETS

MICS3-CBAZ55ZA1P01 | microScan3

SAFETY LASER SCANNERS

Illustration may differ

Ordering information

Type	Part no.
MICS3-CBAZ55ZA1P01	1091038

The system plug is pre-assembled on the underside. It can either be mounted on the rear side or the underside.

Other models and accessories → www.sick.com/microScan3

Detailed technical data

Features

Protective field range	5.5 m
Warning field range	40 m
Number of simultaneously monitored fields	≤ 8 [1)]
Number of fields	128
Number of monitoring cases	128
Scanning angle	275°
Resolution (can be configured)	30 mm 40 mm 50 mm 70 mm 150 mm 200 mm
Angular resolution	0.39°
Response time	≥ 95 ms
Protective field supplement	65 mm

[1)] Protection, warning or contour detection fields.

Safety-related parameters

Type	Type 3 (IEC 61496)
Safety integrity level	SIL2 (IEC 61508) SILCL2 (EN 62061)
Category	Category 3 (EN ISO 13849)
Performance level	PL d (EN ISO 13849)
PFH_D (mean probability of a dangerous failure per hour)	8.0×10^{-8} (EN ISO 13849)
T_M (mission time)	20 years (EN ISO 13849)
Safe state in the event of a fault	The safety outputs via the network are logic 0.

2 OPTO-ELECTRONIC PROTECTIVE DEVICES | SICK

Product data sheet | 2020-07-08 12:35:54
Subject to change without notice

Figure A.1. Technical specicifications of SICK microScan3 laser scanner.

MICS3-CBAZ55ZA1P01 | microScan3
SAFETY LASER SCANNERS

Functions

Restart interlock	✓
Multiple sampling	✓
Monitoring case switching	✓
Simultaneous monitoring	✓
Static protective field switching	✓
Safe contour detection	✓
Contour as a reference	✓
Integrated configuration memory	✓
Measured data output	✓, via Ethernet
Safe SICK device communication via EFI-pro	✓

Interfaces

Connection type	
Voltage supply	1 x male connector, M12, 4-pin, A-coded
Fieldbus, industrial network	2 x M12 female connectors, 4-pin, D-coded
Outputs	
OSSD pairs	0
Safety outputs via network	8
Configuration method	PC with Safety Designer (Configuration and Diagnostic Software)
Configuration and diagnostics interface	USB 2.0, Mini-USB, Ethernet
Fieldbus, industrial network	EFI-pro
Protocol	CIP Safety™
RPI (requested packet interval)	5 ms ... 1,000 ms, multiple of 5 ms
Display elements	Graphic color display, LEDs

Electrical data

Protection class	III (EN 61140)
Supply voltage V_s	24 V DC (16.8 V DC ... 30 V DC)
Power consumption	7 W (without output load)

Mechanical data

Dimensions (W x H x D)	112 mm x 150.8 mm x 111.1 mm (without system plug)
Weight	1.45 kg
Housing material	Aluminum
Housing color	RAL 1021 (yellow), RAL 9005 (black)
Optics cover material	Polycarbonate
Optics cover surface finish	Outside with scratch-resistant coating

Ambient data

Enclosure rating	IP65 (IEC 60529)
Ambient light immunity	≤ 3,000 lx (IEC 61496-3)
Ambient operating temperature	–10 °C ... +50 °C
Storage temperature	–25 °C ... +70 °C

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Subject to change without notice

OPTO-ELECTRONIC PROTECTIVE DEVICES | SICK 3

Figure A.2. Technical specicifications of SICK microScan3 laser scanner.

Vibration resistance		0.35 mm, 10 Hz ... 60 Hz (IEC 60068-2-6, IEC 61496-1, IEC 61496-3) 5 g, 60 Hz ... 150 Hz (IEC 60068-2-6, IEC 61496-1, IEC 61496-3)
Shock resistance		
	Continuous shock	10 g, 16 ms (IEC 60068-2-27, IEC 61496-3)
EMC		IEC 61496-1 IEC 61000-6-2 IEC 61000-6-4

Other information

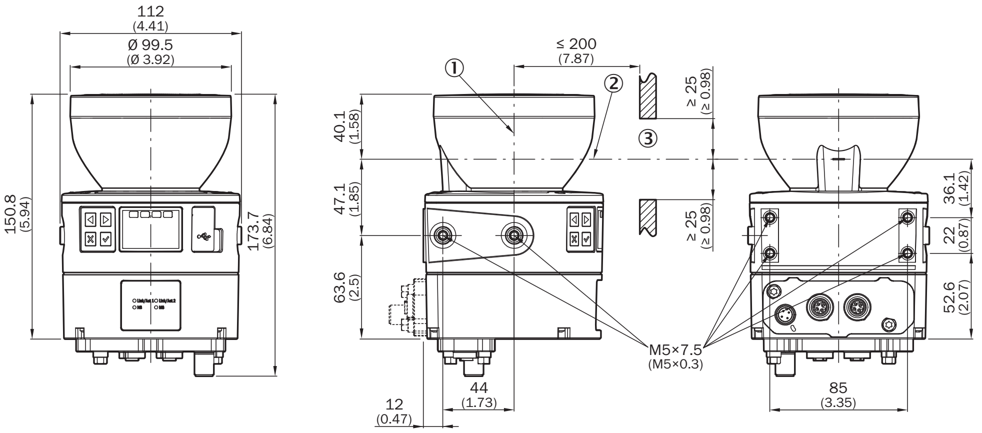
Type of light	Pulsed laser diode
Wave length	845 nm
Detectable remission	1.8% to several 1000%
Laser class	1M (21 CFR 1040.10 and 1040.11, IEC 60825-1)

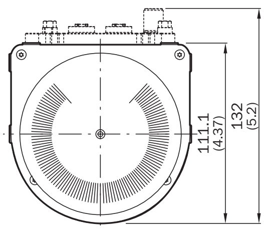
Classifications

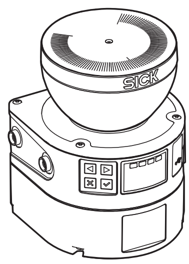
ECl@ss 5.0	27272705
ECl@ss 5.1.4	27272705
ECl@ss 6.0	27272705
ECl@ss 6.2	27272705
ECl@ss 7.0	27272705
ECl@ss 8.0	27272705
ECl@ss 8.1	27272705
ECl@ss 9.0	27272705
ECl@ss 10.0	27272705
ECl@ss 11.0	27272705
ETIM 5.0	EC002550
ETIM 6.0	EC002550
ETIM 7.0	EC002550
UNSPSC 16.0901	39121528

Figure A.3. Technical specicifications of SICK microScan3 laser scanner.

Dimensional drawing (Dimensions in mm (inch))







① Mirror axis of rotation
② Scan plane
③ Required viewing slit

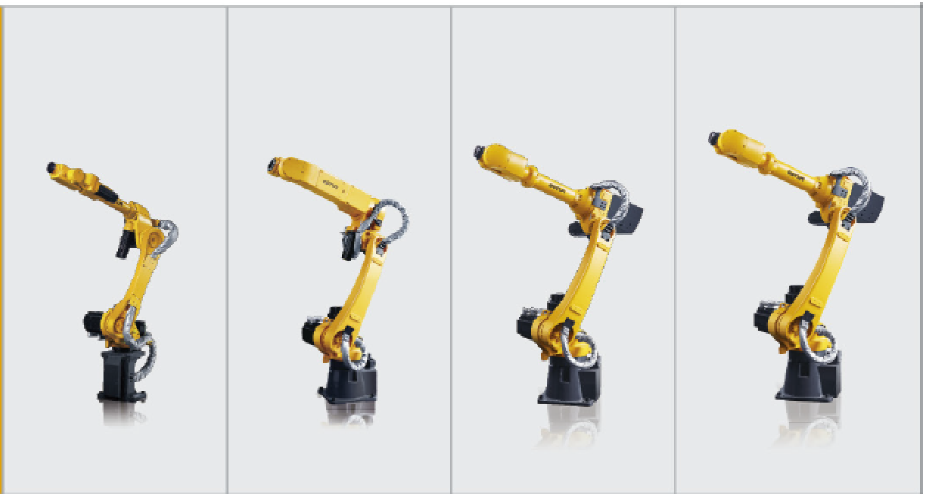
Recommended accessories

Other models and accessories → www.sick.com/microScan3

	Brief description	Type	Part no.
Mounting brackets and plates			
	1 piece, mounting bracket, heavy-duty version, with protection cover, for floor mounting, height adjustment possible from 90 ... 310 mm, scanner tilt angle: ± 5°. Additional mounting brackets are not required., steel, painted (RAL 1021)	Heavy-duty mounting kit for floor mounting	2102289
	1 piece, mounting bracket	Mounting kit 1a	2073851
	1 piece, mounting bracket with protection of optics hood	Mounting kit 1b	2074242

Figure A.4. Technical drawings of SICK microScan3 laser scanner.

6-axis articulated robot



Model		ER4-1450	ER6-1600	ER10-1600	ER16-1600
Maximum load (kg)		4	6	10	16
Reach of arm (mm)		1450	1600	1600	1600
Repeatability accuracy (mm)		±0.1	±0.08	±0.1	±0.1
Potection grade		IP65	IP65	IP65	IP65
Working range	axis 1	±180°	±180°	±180°	±180°
	axis 2	-70~+160°	-60°~+140°	-60°~+140°	-60°~+140°
	axis 3	-200°~+80°	-155°~+80°	-170°~+80°	-170°~+80°
	axis 4	±170°	±170°	±360°	±360°
	axis 5	±135°	±180°	-130°~+120°	-130°~+120°
	axis 6	±360°	±360°	±360°	±360°
Maximum speed	axis 1	156°/s	148°/s	148°/s	148°/s
	axis 2	156°/s	109°/s	109°/s	109°/s
	axis 3	234°/s	214°/s	214°/s	214°/s
	axis 4	360°/s	440°/s	368°/s	368°/s
	axis 5	520°/s	435°/s	385°/s	385°/s
	axis 6	540°/s	520°/s	462°/s	462°/s
Weight (kg)		145	164	170	170
Operation power of the robot (kW)		2	2.2	2.6	2.6
Mounting position		floor/ceiling	floor/ceiling	floor/ceiling	floor/ceiling

Figure A.5. Technical specicifications of ESTUN ER16 industrial robot.

KeTop T70

Effective mobile operation, brilliant visualization

State-of-the-art optics and best ergonomics

The plain, joint-free installation of the KeTop T70 display allows best user experience – even with frequent changes between touch display and keyboard operation. Operating elements placed on the edge of the housing can also be activated easily and precisely. Thanks to the flush display installation, unintended touch triggers due to dirt particle accumulations are excluded, as are the burning in of sweat spatters.

The high-resolution display is installed in portrait format, which enables an especially compact housing design and makes a device that lies perfectly in the hand. If necessary, the touch screen can also be operated with a stylus, which is kept ergonomically and securely in an opening on the rear side of KeTop T70.

Data can be backed up on a USB stick. Smaller sticks will also fit under the closed USB cover and are thus fully IP 65-protected.

Technical data

Housing
- LxWxH [mm]: approx. 250 x 210 x 50
- Weight: approx. 960 g (without cable)
- Color: RAL 7016 Anthracite grey
- Material: ABS-PC
- Protection class: IP 65

Display
- Size: 7“ (153 x 90 mm)
- Resolution: WSVGA. 600 x 1024 pixels, 16 million colors
- Touch screen: analog resistive

Operating elements
- Selection switch 4 levels
- Rotary switch 16 levels
- Key switch
- Push buttons
- Membrane keyboard with max.
  20 tactile keys on the front side
  12 tactile keys on the rear side

Safety elements
- 3-level enabling button (2-circuit)
- Emergency stop button (2-circuit)

Processor
- Cortex A9® single and dual core

Memory
- 4 GB Flash, at least 1 GB RAM

Communication interface
- Ethernet 10/100 Mbit/s

Data back-up
- USB 2.0

Power supply
- 24 V DC

Current consumption
- max. approx. 400 mA at 24 V DC

Ambient conditions
- Operating temperature:
  0 °C to 40 °C dual core
  0 °C to 45 °C single core
- Storage temperature: -25 °C to 70 °C
- Relative humidity: 5% to 95% (non-condensing)
- Vibration resistance / shock-proof
  according to EN 61131-2

Certifications
- UL, CE

Options
- Magnetic holder

KEBA®

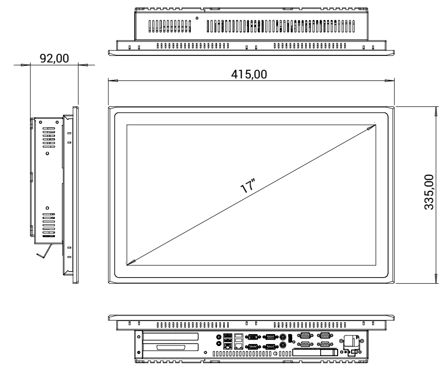
Automation by innovation.

KEBA AG, Gewerbepark Urfahr, A-4041 Linz, Phone: +43 732 7090-0, Fax: +43 732 730910, keba@keba.com, www.keba.com

Figure A.6. Technical specicifications of KeTop T70 teach pendant.

artech
art of technology

IPC-417-Serisi



Sistem	
CPU	Intel® Celeron j1900 / Intel® Icore I5/I7
Cache	2nd Level depends on CPU
Memory	2 x DDR3 SoDIMM maks. 4GB / 8GB / (16GB Opsiyonel)
Video RAM	Maks 128 MB paylaşımlı hafıza
Chipset	Intel® Soc / QM77
Watchdog Timer	255 Level Reset
System Fan	N.A.

I/O	
Serial Port	3 x RS-232 ports
Parallel Port	SPP/EPP/ECP(Opsiyonel)
USB Port	4 x USB 2.0 uyumlu
KB / MS	1 x PS2 K/B and Mouse
LAN	Dual LAN; Dual gigabit ethernet 10/100/1000
Kablosuz LAN	802.11 b / g / n (Opsiyonel)
Ses	Line in & out (AC'97 codec audio)
Genişleme Yuvası	PCI , MiniPCIe

Veri Saklama	
HDD / Type	Titreşime Karşı Dayanımlı Yuvada 2.5" HDD
SSD	64 GB / 128GB / 256 GB

Besleme	
Giriş	220VAC veya 24VDC

LCD Ekran	
Boyut / Tip	17" LVDS
Maks. Çözünürlük	1280 x 1024, XGA
Pixel Pitch	0.297mm x 0.297mm
Maks. Renk	16.7 M
Parlaklık (cd/m2)	350cd
Kontrast Oranı	1000/1
Görüş Açısı	160°(H),160°(V)
Arka Işık MTBF	50,000 hours
Dokunmatik Ekran	17" Touch - Rezistif

Ekstra Video Çıkışı	
Tip	HDMI/(DP/DVI/VGA Opsiyonel)
Maks. Çözünürlük	1920x1080/(2560x1600 Opsiyonel)

Mekanik & Çevresel Özellikler	
Çalışma Sıcaklığı	0 ~ 60°C
Depolama Rutubeti	5 ~ 95% (non-condensing)
Kasa	Ağır Şartlara Dayanımlı Paslanmaz Metal Kasa
Ön Çerçeve	IP65 Aluminyum
Ağırlık	Ekran ölçüsüne göre değişken (1—5 kg)
Boyutlar (WxHxD)	Ekran ölçüsüne göre değişken
Montaj	Panel ve Duvar Montaj

Sipariş Kodu

CPU	PSU	RAM	HDD	Wi-fi
J1900	AC - 220 VAC	R4	500 GB HDD(Opsiyonel)	Opsiyonel
i5	DC - 24 VDC	R8	64 GB SSD	
i7		R16	128 GB SSD	
			256 GB SSD	

ÇİZGİ TEKNOLOJİ
YERLİ ÜRETİM
CE
Windows Embedded Silver Partner
RoHS COMPLIANT

Figure A.7. Technical specicifications of IPC used as ROS Computer.