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Design and simulation of an event-driven ABB Robotic pick-and-place cell with buffer-based production management

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Dedication

We dedicate this work to our dear parents, whose support, patience, and encouragement have accompanied us throughout our studies. Their sacrifices and guidance have always been a source of strength for us.

We also dedicate this thesis to our families, who stood beside us during the difficult moments and gave us the motivation to continue until the completion of this work.

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Finally, we dedicate this modest work to every person who supported us, directly or indirectly, and contributed in any way to the achievement of this project.

Abstract:

This thesis focuses on the design and simulation of an adaptive pick-and-place system using an ABB robotic arm. The proposed application concerns the handling of photovoltaic strings and their accurate placement inside solar panel frames. Since photovoltaic components are fragile and require precise positioning, the robotic system must ensure stable motion, safe gripping, and collision-free operation. For this purpose, an ABB industrial robot is selected and integrated into a virtual workstation composed of a conveyor, a buffer area, and an assembly station.
The work is developed using ABB RobotStudio for modeling, simulation, and validation of the robotic cell, while RAPID programming is used to define robot movements, gripper control, and input/output logic. The adaptive aspect of the system is based on the robot's ability to react to workstation conditions. When the frame is available, the robot places the photovoltaic string directly into its position. When the frame is not available, the robot transfers the string to a temporary buffer and retrieves it later when the process can continue. This strategy helps maintain production continuity and reduces unnecessary waiting time. The simulation results allow verification of reachability, trajectory feasibility, and safe operation before real implementation.

Keywords: ABB robotic arm, adaptive control, pick-and-place, RobotStudio, RAPID, photovoltaic strings, industrial automation.

الملخص:

تركز هذه المذكرة على تصميم ومحاكاة نظام روبوتي تكيفي لتنفيذ عمليات الالتقاط والوضع باستعمال ذراع روبوتية من نوع .ABB يتعلق التطبيق المقترح بمناولة السلاسل الكهروضوئية ووضعها بدقة داخل إطارات الألواح الشمسية. ونظرا لأن هذه المكونات حساسة وقابلة للتلف، فإن النظام الروبوتي يحتاج إلى حركة مستقرة، ومسك آمن، وتموضع دقيق، مع تفادي التصادم داخل منطقة العمل. لهذا الغرض، تم اختيار روبوت صناعي من ABB ودمجه داخل محطة عمل افتراضية تتكون من ناقل، ومنطقة تخزين مؤقت، ومحطة تجميع.

تم إنجاز هذا العمل باستعمال برنامج ABB RobotStudio من أجل نمذجة ومحاكاة والتحقق من الخلية الروبوتية، بينما استعملت لغة RAPID لبرمجة حركات الروبوت والتحكم في القابض وإشارات الإدخال والإخراج. يتمثل الجانب التكيفي في قدرة النظام على تغيير سلوكه حسب حالة محطة العمل. فإذا كان إطار اللوح الشمسي متاحا، يقوم الروبوت بوضع السلسلة الكهروضوئية مباشرة في مكانها. أما إذا لم يكن الإطار متاحا، فينقل الروبوت السلسلة إلى منطقة التخزين المؤقت، ثم يسترجعها لاحقا عند توفر الإطار. تساعد هذه الاستراتيجية على الحفاظ على استمرارية الإنتاج وتقليل أوقات الانتظار غير الضرورية. كما تسمح المحاكاة بالتحقق من قابلية الوصول، وصحة المسارات، وسلامة التشغيل قبل الانتقال إلى التطبيق الحقيقي.

الكلمات المفتاحية :ذراع روبوتيةABB ، تحكم تكيفي، الالتقاط والوضع، RobotStudio، RAPID، سلاسل كهروضوئية، أتمتة صناعية.

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List of Abbreviations:

ABB: Asea Brown Boveri
AI: Artificial Intelligence
CAD: Computer-Aided Design
CNC: Computer Numerical Control
DO: Digital Output
DI: Digital Input
HMI: Human-Machine Interface
I/O: Input / Output
IEC: International Electrotechnical Commission
IFR: International Federation of Robotics
IP: Ingress Protection
IRB: Industrial Robot
ISO: International Organization for Standardization
PLC: Programmable Logic Controller
PV: Photovoltaic
RAPID: ABB Robot Programming Language
SCARA: Selective Compliance Assembly Robot Arm
TCP: Tool Center Point
VC: Virtual Controller

General Introduction

General Introduction

Industrial automation has become an important part of modern manufacturing systems. In many production lines, companies are trying to improve productivity, reduce human effort, and obtain more stable product quality. For this reason, industrial robots are now widely used in repetitive and precise operations such as material handling, assembly, packaging, welding, and pick-and-place tasks. These robots can work with high speed and repeatability, which makes them suitable for applications where accuracy and cycle time are important.

Among these applications, pick-and-place operations are considered one of the most common uses of robotic manipulators. The basic idea is simple: the robot picks an object from one position and places it in another required position. However, in real industrial conditions, this task can become more complex. The robot must detect the object, move safely inside the workspace, avoid collisions, control the gripper correctly, and place the part with good precision. If the production flow changes, for example when the next station is not ready or when objects arrive irregularly, the system also needs a suitable control strategy to keep the process stable.

ABB industrial robots are widely used in automation because of their precision, flexibility, and compatibility with advanced programming and simulation tools. In this work, the ABB robotic environment is selected because it offers both the physical robot technology and the software tools required for virtual design. ABB RobotStudio allows the robotic cell to be created and tested before real implementation, while the RAPID programming language is used to define robot movements, input/output signals, and the control sequence of the task.

The present thesis focuses on the design and simulation of an automated pick-and-place system using an ABB robotic arm. The proposed application is related to the handling of photovoltaic strings and their placement inside solar panel frames. This type of task requires careful handling because photovoltaic components are fragile and must be positioned accurately. The system also includes a conveyor, a temporary buffer area, and an assembly station. The buffer is used to improve continuity when there is a difference between the arrival of photovoltaic strings and the availability of the panel frame.

The main idea of adaptive control in this project is not limited to moving the robot from one fixed point to another. The system must react according to the state of the workstation. For example, if the frame is available, the robot places the photovoltaic string directly in the frame. If the frame is not available, the robot can transfer the string to the buffer area. Later, when the

frame becomes available again, the robot can retrieve the stored string and continue the assembly operation. In this way, the control logic adapts to the production condition and helps reduce unnecessary waiting time.

The main objective of this work is to design, program, and simulate an ABB robotic arm for automated pick-and-place tasks, with a particular focus on accuracy, workspace organization, gripper control, and adaptive operating logic. To achieve this objective, the study first presents the basic concepts of industrial robotics and pick-and-place systems. Then, it introduces ABB robotic systems, including the ABB robot, RAPID language, RobotStudio software, and adaptive control principles. Finally, it develops the proposed robotic cell, explains the selection of the robot and end-effector, describes the control sequence, and validates the system through simulation.

This thesis is organized into four chapters. The first chapter presents general concepts related to industrial automation, industrial robots, and pick-and-place systems. The second chapter focuses on ABB robotic systems and the tools used in this project, especially the ABB IRB 2600 robotic arm, the robot controller, RAPID programming, RobotStudio software, and adaptive control. The third chapter is dedicated to the design and simulation of the proposed system. It includes the system requirements, robot selection, end-effector design, workstation layout, adaptive control logic, RAPID implementation, and simulation validation. The fourth chapter presents the implementation, station logic, RAPID program architecture, simulation execution, results, performance analysis, limitations, and possible improvements.

Through this work, the aim is to show how an ABB robotic arm can be used to perform an automated pick-and-place task in a structured industrial environment. The use of simulation makes it possible to verify robot reachability, movement feasibility, safety, and collision-free operation before moving toward real implementation. Although the work remains mainly based on simulation, it provides a practical basis for future development of a real robotic workstation for photovoltaic panel assembly or similar industrial handling applications.

Chapter I:

Industrial Robotics and Pick-and-Place Systems

I.1 Introduction

Industrial robotics is one of the main fields that supported the development of modern automated production systems. In many factories, robots are no longer used only for heavy or dangerous tasks, but also for operations that require precision, speed, and repeated movements. This is why robotic manipulators are widely found in assembly lines, packaging systems, material handling stations, welding cells, and several other industrial applications.

A robot used in industry is generally designed to perform programmed movements with a high level of repeatability. It can move parts, tools, or products from one position to another according to a predefined sequence. With the development of sensors, controllers, and programming tools, industrial robots have also become more flexible and easier to integrate into different production environments.[1]

Pick-and-place tasks represent one of the simplest but most important applications of industrial robots. The principle consists of picking an object from a specific location and placing it in another location with the required position and orientation. Although the task seems basic, its correct execution depends on several elements, such as the robot structure, the end-effector, the control system, the workspace layout, and the detection method used to locate the object.

This chapter presents the general background needed to understand the proposed robotic system. It begins with industrial automation and its role in manufacturing. Then, it introduces industrial robots, their main classifications, and their essential components. After that, the chapter focuses on pick-and-place systems, including their operating principle, main components, advantages, limitations, and technical challenges. This theoretical basis is important before moving to ABB robotic systems and the simulation tools used in the following chapter.[2]

I.2 Industrial Automation

Industrial automation can be understood as the use of machines, control systems, sensors, and software to carry out production tasks with limited human intervention. In a traditional production system, most operations depend directly on the worker’s physical effort and attention. In an automated system, many of these operations are performed by controlled equipment such as conveyors, programmable logic controllers, industrial robots, and computerized machines.

Automation is not used only to replace manual work. In practice, it is mainly introduced to make the production process more stable, faster, and easier to control. A well-designed automated system can repeat the same operation many times with almost the same result. This is especially important in industries where quality, safety, and production rate are important factors.[2]

I.2.1 Definition of Automation

Automation refers to the application of control technologies to operate machines and processes with minimum direct human participation. These technologies may include electrical control circuits, PLCs, sensors, actuators, industrial computers, and robotic systems. The role of the operator does not disappear completely, but it changes. Instead of performing the task manually, the operator usually supervises the process, adjusts parameters, and intervenes when an abnormal situation occurs.

In industrial environments, automation can be applied at different levels. A simple automated system may consist of a conveyor controlled by sensors and motors. A more advanced system may include robots, machine vision, safety devices, and communication with production management software. This shows that automation is not one single technology, but a combination of several elements working together.[2]

I.2.2 Importance of Automation in Industry

The importance of automation appears clearly in modern manufacturing. Companies need to produce faster while keeping product quality stable. Manual work can be affected by fatigue, variation in skill, and human error. Automated machines, on the other hand, can execute repetitive operations with better regularity, especially when the task requires precise movements or fixed timing.

Automation also improves the use of production resources. Machines can work for long periods, and production lines can be organized to reduce waiting time between operations. In many cases, automation helps reduce waste, improve traceability, and make the process easier to monitor. This is why automated systems are used in sectors such as automotive manufacturing, electronics, food processing, logistics, and renewable energy production.

Another important point is safety. Some industrial tasks expose workers to risks such as heavy loads, sharp tools, high temperatures, toxic materials, or repetitive movements. By assigning these tasks to machines or robots, the operator can be kept away from dangerous areas. This

does not remove all risks, but it makes the workplace easier to control when safety rules are correctly applied.[2]

I.2.3 Benefits and Limits of Industrial Automation

Industrial automation offers several benefits. It increases productivity by reducing manual delays and improving cycle time. It also improves repeatability because machines can perform the same movement or operation many times with small variation. In addition, automation can improve product quality, reduce production errors, and help companies respond to high production demand.

However, automation also has some limits. The first limitation is the initial cost. Installing an automated system usually requires investment in machines, robots, sensors, controllers, software, and training. Another limitation is the need for technical maintenance. If the system is not maintained correctly, failures may stop the whole production line. Automation can also be less flexible when the product changes frequently, unless the system is designed from the beginning to support reconfiguration.

For this reason, the choice of automation must be based on a real technical need. In the case of robotic pick-and-place systems, automation becomes useful when the task is repetitive, requires good positioning accuracy, or needs to be performed continuously. This makes industrial robots suitable for applications where objects must be transferred from one place to another in a controlled and reliable way.[3]

I.3 Industrial Robots

Industrial robots are one of the main elements used in modern automated production systems. They are introduced in factories when the task requires repeated movements, good accuracy, high speed, or safe handling of objects. In many production lines, the robot works with other equipment such as conveyors, sensors, controllers, grippers, and safety devices. So, it should not be considered only as a mechanical arm, but as a complete automated system.

In industrial applications, robots are used for several tasks such as material handling, assembly, packaging, welding, painting, palletizing, and machine loading. Among these tasks, pick-and-place operations are very common because they depend mainly on moving an object from one position to another in a controlled way. The performance of this operation depends on the robot structure, its workspace, the selected end-effector, and the control strategy used to coordinate the motion.[1]

I.3.1 Definition of Industrial Robots

An industrial robot can be defined as an automatically controlled and reprogrammable manipulator, programmable in several axes, and used to perform industrial tasks. This definition shows three important ideas. First, the robot is controlled automatically by a controller. Second, it can be reprogrammed to execute different tasks. Third, it is able to move in several axes, which allows it to reach different positions inside its workspace.

The term “reprogrammable” is very important in robotics. It means that the robot can be adapted to another operation by changing the program instead of replacing the whole machine. For example, the same robotic arm may be used for handling parts, then later it can be reprogrammed for assembly or packaging if the tool and the workstation allow it. This flexibility is one of the main reasons why robots are widely used in industry.[4]

In most cases, an industrial robot follows a sequence of programmed instructions. These instructions define the robot targets, movement type, speed, tool position, and sometimes input/output signals. The robot controller executes these instructions and sends commands to the actuators in order to move the different joints. For this reason, robot performance depends not only on the mechanical design, but also on the control system and the quality of programming.[3]

I.3.2 Brief History of Robotics

The idea of machines capable of imitating human actions is not new, but industrial robotics started to develop seriously during the twentieth century with the growth of automation. The first industrial robots were mainly designed to perform repetitive and dangerous tasks, especially in automotive factories. One of the most known early examples is the Unimate robot, which was used for handling hot metal parts in a production line. This type of application helped reduce direct human exposure to dangerous working conditions.[8]

After the first industrial applications, robot technology developed quickly. Robots became more accurate, faster, and easier to control. Electrically driven robots replaced many older hydraulic systems in several applications because they offered better control and cleaner operation. Later, articulated robots, SCARA robots, Cartesian robots, and parallel robots became common in different industrial sectors.[3]

With the progress of electronics, sensors, and computer control, industrial robots became more flexible. They were no longer limited to simple repetitive movements. They could be

programmed with more complex trajectories, connected to external sensors, and integrated with production systems. Today, industrial robots are used in many fields such as automotive manufacturing, electronics, food industry, logistics, metal processing, and renewable energy production.[7]

I.3.3 Classification of Industrial Robots

Industrial robots can be classified in different ways. The most common classification is based on their mechanical structure, because the structure determines the robot workspace, movement capability, and suitable applications. The main industrial robot structures are illustrated in the following figures. These figures help clarify the difference between configurations, especially in terms of workspace shape and motion capability.

Articulated robots are the most widely used type in industry. They are composed of several rotary joints, usually with six axes. Their structure is close to a human arm, which gives them a large and flexible workspace. Because of this flexibility, articulated robots are used in welding, material handling, assembly, painting, and pick-and-place applications.[3]

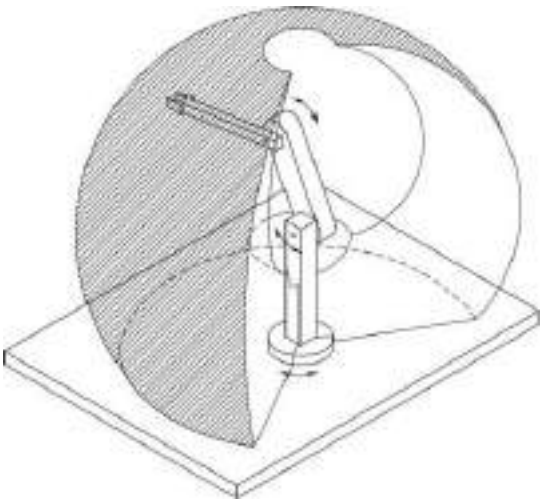


Figure I.1: Workspace of an articulated industrial robot.[3]

SCARA robots are designed mainly for fast horizontal movements with vertical insertion capability. They are usually used in assembly and packaging tasks, especially when the operation requires speed and repeatability in a limited workspace. SCARA robots are common in electronics manufacturing and small-part handling.[5]

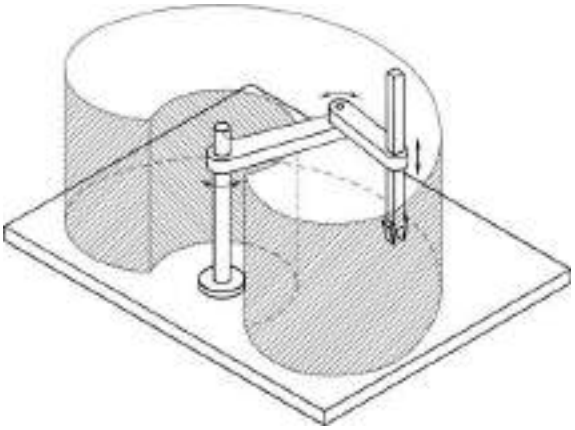


Figure I.2: Workspace of a SCARA robot.[3]

Cartesian robots, also called gantry robots, move along three linear axes. Their structure is simple and rigid, which makes them suitable for applications that need straight movements and good positioning accuracy. They are often used in material handling, machine loading, and large-area pick-and-place operations.

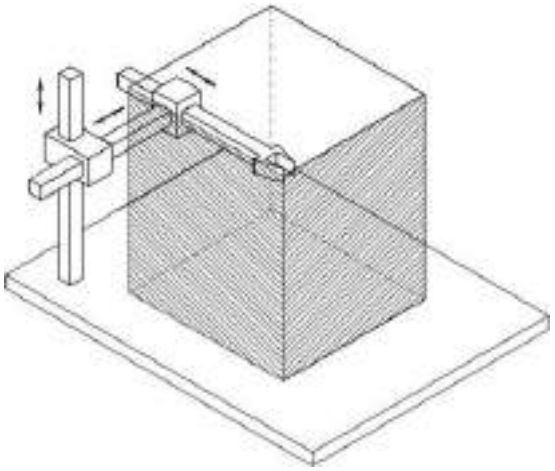


Figure I.3: Workspace of a Cartesian robot.[3]

Cylindrical robots use a combination of rotary and linear movements, creating a cylindrical workspace. They are less common than articulated and SCARA robots in modern production lines, but they can still be useful in some handling and machine-tending applications.

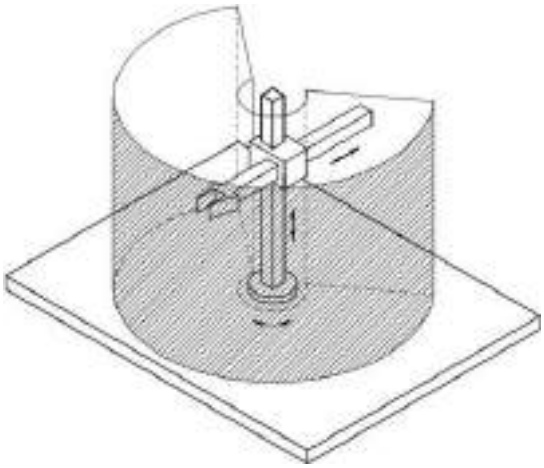


Figure I.4: Workspace of a cylindrical robot.[3]

Spherical robots operate inside a spherical workspace using rotary joints and one linear movement. Their use has decreased compared with modern articulated robots, but they remain important in the classification of robot structures because they represent a different way of generating motion.[3]

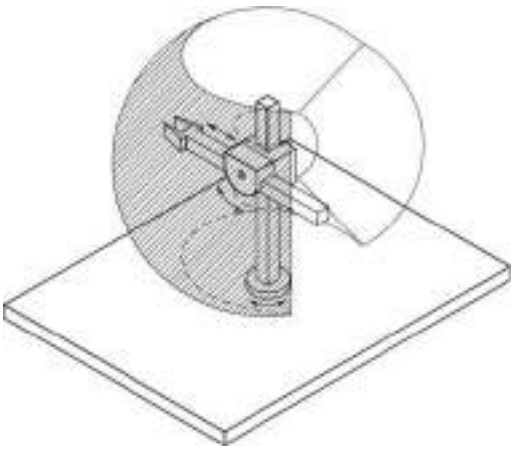


Figure I.5: Workspace of a spherical robot.[3]

Parallel robots, such as delta robots, are based on a closed kinematic structure. Several arms are connected between the base and the moving platform. This structure gives them high speed and good dynamic performance, which makes them very suitable for high-speed pick-and-place tasks. However, their workspace is generally smaller than that of articulated robots.[5]

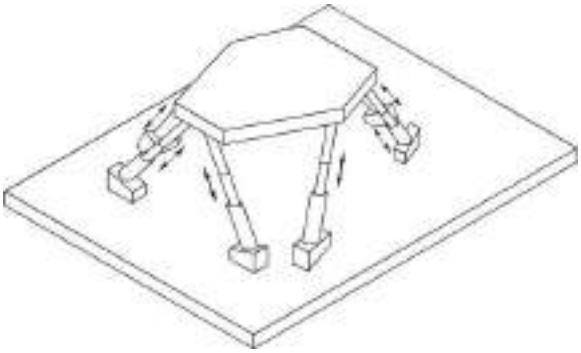


Figure I.6: Structure of a parallel robot.[3]

From these different types, articulated robots are often selected when the application requires a large workspace and flexible motion. This explains why they are widely used in industrial handling systems and why an ABB articulated robot is suitable for the pick-and-place application studied in this thesis.[6]

I.3.4 Components of an Industrial Robot

An industrial robot is composed of several mechanical, electrical, and control elements. Each element has a specific role, and the final performance of the robot depends on the correct coordination between them.

The **manipulator** is the mechanical structure of the robot. It consists of links connected by joints. The links form the rigid parts of the robot, while the joints allow relative motion between these links. Depending on the robot configuration, the joints can be rotary or linear. In articulated robots, most joints are rotary, which allows the robot to move with high flexibility.

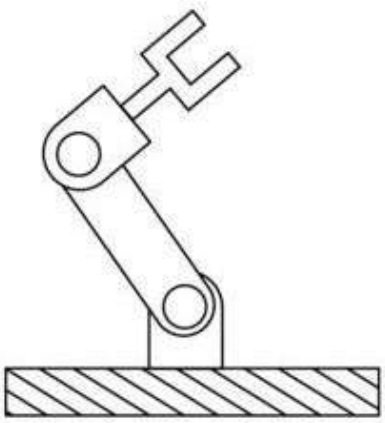


Figure I.7: Kinematic structure of a serial manipulator.[7]

Some robots use a serial structure, where the links are connected one after another from the base to the end-effector. Other robots, such as parallel robots, use a closed-chain structure,

where several links support the moving platform at the same time. Each structure has its advantages. Serial manipulators usually offer a larger workspace, while parallel manipulators are often faster and more rigid.[5]

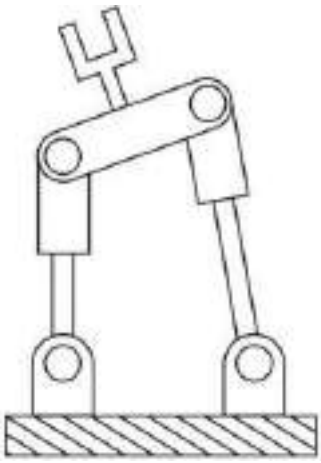


Figure I.8: Kinematic structure of a parallel manipulator.[7]

The **actuators** are responsible for producing motion. In modern industrial robots, electric servo motors are commonly used because they provide good accuracy, speed control, and energy efficiency. Pneumatic or hydraulic actuators may also be used in some specific cases, but electric actuation remains the most common choice for precise industrial manipulators.

The **transmission system** transfers the actuator motion to the robot joints. It may include gears, belts, reducers, screws, or other mechanical components. Its role is to adapt the torque and speed according to the needs of each axis. A good transmission system helps the robot move smoothly and maintain positioning accuracy.

The **sensors** provide information about the robot and its working environment. Internal sensors, such as encoders, measure joint positions and speeds. External sensors, such as proximity sensors, force sensors, and cameras, can be used to detect objects or monitor the process. In pick-and-place systems, sensors are very useful because they help confirm object presence and support the synchronization between the robot and the workstation.[6]

The **controller** is the main unit that manages the robot operation. It reads the robot program, calculates the required movements, sends commands to the motors, and receives feedback from sensors. It also manages input/output signals, safety functions, and communication with other industrial equipment. Without the controller, the robot cannot perform coordinated movements.

The **end-effector** is the tool mounted at the wrist of the robot. It is the part that interacts directly with the object or the process. In pick-and-place applications, the end-effector is generally a

gripper. It may be mechanical, vacuum-based, magnetic, or adaptive, depending on the shape, weight, and material of the object to be handled.



Figure I.9: Main structural components of an ABB industrial robot.[9]

In a complete robotic cell, these components are not used separately. The manipulator, controller, sensors, end-effector, and surrounding equipment must work together. This integration is what allows the robot to perform reliable industrial tasks such as the automated pick-and-place operation studied in this work.[5]

I.4 Pick-and-Place Systems

Pick-and-place systems are among the most common applications of industrial robots. Their main function is to take an object from one position and place it in another position according to a defined sequence. At first, this operation may seem simple, but in a real production environment it requires good coordination between the robot, the gripper, the sensors, the controller, and the workstation layout.

In many industries, pick-and-place robots are used to reduce manual handling and improve production regularity. They are especially useful when the task is repetitive, when the objects must be placed accurately, or when the operation must be performed continuously for long periods. These systems are found in packaging lines, electronic assembly, food processing, sorting systems, machine loading, and photovoltaic panel manufacturing.[2]

I.4.1 Definition and Principle of Operation

A pick-and-place system is an automated handling system designed to pick an object from a source location and place it in a target location. The source location may be a conveyor, a table, a tray, or a storage zone. The target location may be another conveyor, a fixture, a box, a pallet, or an assembly position.

The basic cycle of a pick-and-place task generally follows these steps:

1. Detection of the object at the pickup position.
2. Movement of the robot toward the object.
3. Activation of the gripper or vacuum system.
4. Lifting and transportation of the object.
5. Movement toward the target position.
6. Release of the object at the required location.
7. Return of the robot to the home position or to the next pickup point.

In simple systems, the pickup and placement positions are fixed and known in advance. In more advanced systems, sensors or cameras are used to detect the position and orientation of the object. This allows the robot to adapt to small variations in object location and improves the flexibility of the system.

The operating sequence of a pick-and-place task can be represented by a simple flow diagram, as shown in Figure I.10. This kind of figure helps to understand the order of actions executed by the robot during one complete cycle.[3]

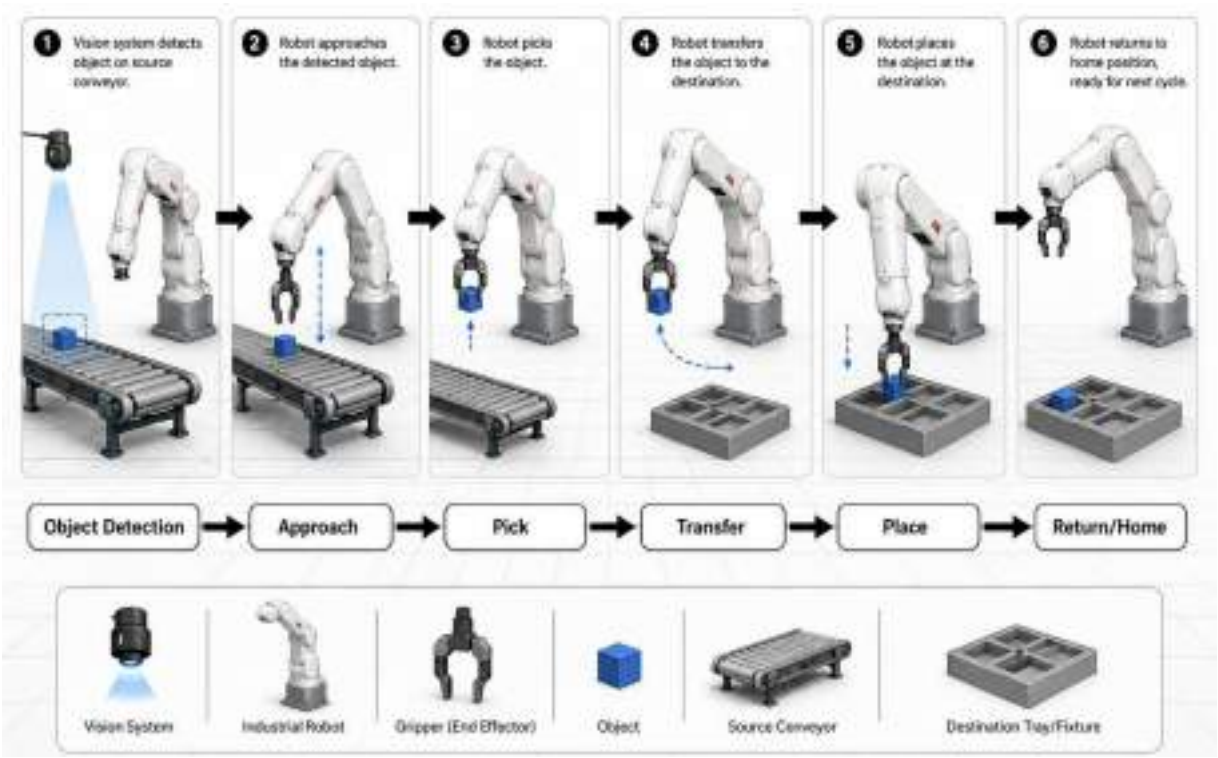


Figure I.10: Basic sequence of a robotic pick-and-place operation.[3]

I.4.2 Main Components of Pick-and-Place Systems

A robotic pick-and-place system is not composed only of the robot arm. It is usually a complete automated cell where several elements work together. The most important elements are the robotic arm, the end-effector, the sensing system, the controller, the conveyor or positioning device, and the safety equipment.

The **robotic arm** provides the movement required to transfer the object from one position to another. Depending on the application, the robot may be articulated, SCARA, Cartesian, or parallel. The choice depends on the payload, reach, required speed, workspace size, and positioning accuracy.

The **end-effector** is the tool mounted at the end of the robot arm. It holds the object during the transfer operation. In pick-and-place applications, the end-effector is generally a gripper. It can be mechanical, vacuum-based, magnetic, or adaptive, depending on the object characteristics.

The **sensing system** is used to detect object presence, confirm the state of the gripper, and sometimes identify the object position. In basic applications, simple proximity sensors may be enough. In more complex applications, vision systems are used to locate randomly placed objects or verify their orientation.[3]

The **controller** executes the robot program and coordinates the movement sequence. It also manages input and output signals, such as object detection signals, vacuum activation, and safety conditions. In many industrial cells, the robot controller communicates with a PLC or other automation equipment.

The **conveyor or positioning device** presents the object to the robot and may also move the finished product to the next station. Correct positioning of the conveyor is important because it affects robot reachability, path length, and cycle time.

The **safety system** protects operators and equipment. It may include emergency stops, safety barriers, light curtains, safety zones, and collision supervision. These elements are necessary because the robot can move at high speed and with significant force.[2]

A simplified organization of the main components of a robotic pick-and-place system is shown in Figure I.11.

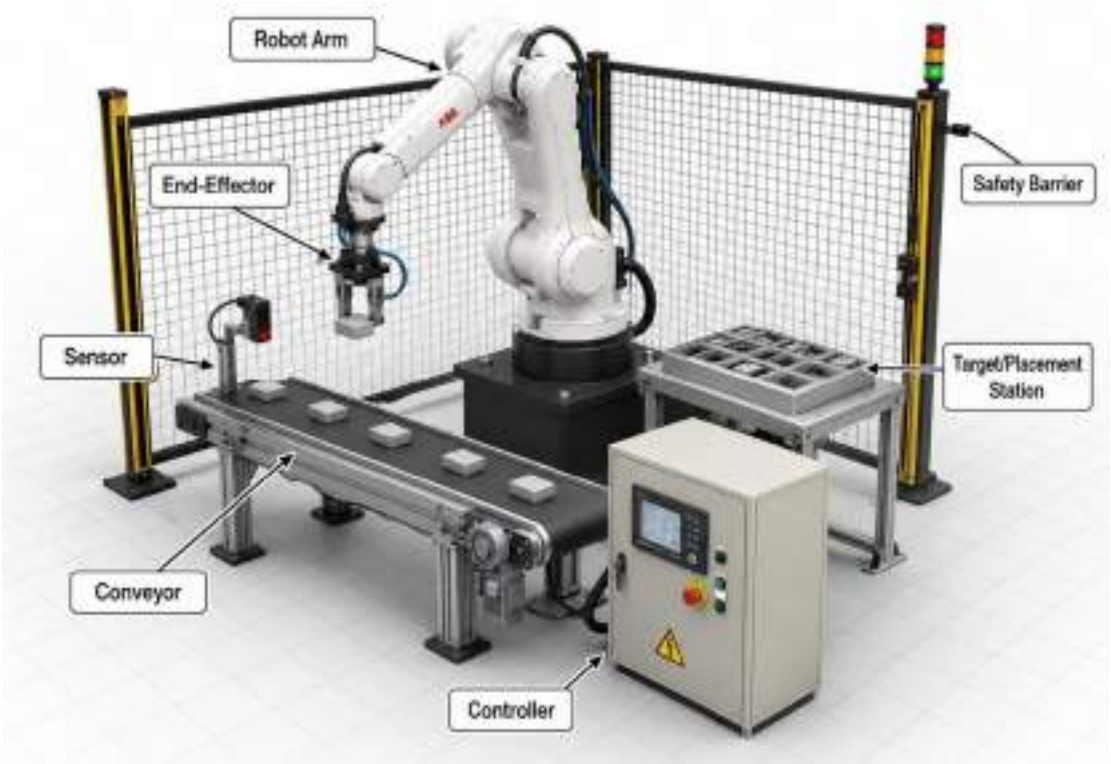


Figure I.11: Main components of a robotic pick-and-place system.

Table I.1: Main components of a pick-and-place system.

Component	**Main role**	**Example**
Robotic arm	Provides motion and positioning	ABB articulated robot, SCARA robot, delta robot
End-effector	Holds and releases the object	Vacuum gripper, mechanical gripper
Sensors	Detect object presence and system state	Proximity sensor, vision camera
Controller	Executes the program and coordinates signals	Robot controller, PLC
Conveyor or fixture	Presents or receives the object	Belt conveyor, positioning table
Safety devices	Protect operators and equipment	Emergency stop, safety fence, light curtain

I.4.3 End-Effectors Used in Pick-and-Place Tasks

The end-effector is one of the most important elements in a pick-and-place system because it is the part that comes into direct contact with the object. A correct choice of end-effector improves the reliability of the operation, while a poor choice can cause slipping, product damage, inaccurate placement, or longer cycle time.

Mechanical grippers use fingers or jaws to hold the object. They are suitable for rigid objects that can resist contact force. Their main advantage is their strong and stable gripping capability. However, they may not be suitable for fragile objects if the gripping force is not controlled correctly.

Vacuum grippers use suction cups and vacuum pressure to hold the object. They are commonly used for flat or smooth objects, such as sheets, boxes, glass, and photovoltaic components. Their advantage is that they reduce mechanical pressure on the object surface. This makes them useful when the product is fragile or must not be scratched.[8]

Magnetic grippers are used for ferromagnetic materials such as steel sheets and metallic parts. They are simple and fast, but they cannot be used for non-magnetic objects. For this reason, they are not suitable for photovoltaic strings or glass-based components.

Adaptive grippers are designed to adjust their shape or fingers according to the object geometry. They offer better flexibility when different object shapes must be handled in the same

workstation. However, they are generally more complex and more expensive than simple grippers.

For the application studied in this thesis, the handled objects are photovoltaic strings. These components are relatively fragile and require careful manipulation. For this reason, a vacuum-based end-effector is more suitable than a mechanical gripper, because it can hold the object with less direct mechanical stress.[3]

I.4.4 Advantages and Limitations

Pick-and-place automation offers several advantages in industrial production. It improves productivity because the robot can repeat the same operation continuously with stable performance. It also improves repeatability, since the robot can place objects in the same position many times with small variation.

Another important advantage is safety. Robots can perform repetitive handling tasks and reduce direct human intervention in the production area. This is useful when the task is tiring, fast, or risky for the operator. In addition, robotic handling can reduce product damage if the gripper and motion parameters are correctly selected.

Pick-and-place systems also help improve production organization. They can be integrated with conveyors, buffers, sensors, and assembly stations. This makes it possible to create a more continuous production flow.[2]

However, these systems also have limitations. The first limitation is the initial cost. A robotic cell requires investment in the robot, gripper, sensors, controller, safety equipment, software, and integration. Another limitation is maintenance. Vacuum cups, sensors, cables, motors, and mechanical parts need regular inspection to avoid unexpected stops.

Flexibility can also be a problem if the system is designed for only one product type. When the product shape, size, or position changes, the robot program and the end-effector may need modification. For this reason, modern pick-and-place systems often use sensors, vision systems, and adaptive control logic to improve flexibility.[8]

I.4.5 Technical Challenges

Several technical challenges must be considered when designing a robotic pick-and-place system. One of the first challenges is object detection. The robot must know when the object is

present and where it is located. If the object is not correctly positioned, the robot may fail to grip it or may place it incorrectly.[3]

Gripping reliability is another important challenge. The gripper must hold the object during acceleration, transportation, and deceleration. If the gripping force is too weak, the object may fall. If it is too strong, the object may be damaged. This point is especially important when handling fragile components.[1]

Trajectory planning also affects system performance. The robot path must be safe, smooth, and short enough to reduce cycle time. Poorly planned trajectories can cause unnecessary movements, vibration, or collision with surrounding equipment.

Synchronization with the production line is also necessary. The robot must work in coordination with conveyors, sensors, buffers, and assembly stations. If one element of the system is delayed, the robot may remain in a waiting state. This reduces productivity and may disturb the production flow.

In the present work, this issue is important because the robot must place photovoltaic strings inside a solar panel frame. If the frame is not available, the robot should not stop the entire process. Instead, the string can be stored temporarily in a buffer area and retrieved later when the frame becomes available. This adaptive operating logic helps maintain continuity and makes the pick-and-place system more flexible.[24]

I.5 Industrial Applications of Pick-and-Place Robots

Pick-and-place robots are used in many industrial sectors because they can perform repetitive handling tasks with good speed and repeatability. Their role is mainly to transfer products, components, or materials between different positions in a production line. The exact configuration of the robot depends on the application, the object characteristics, the required cycle time, and the available workspace.[2]

One common application is packaging. In packaging lines, robots are used to pick products from conveyors and place them into boxes, trays, or containers. This type of operation is common in the food industry, pharmaceutical production, cosmetics, and consumer goods. Delta robots and SCARA robots are often used in these applications because of their high speed and compact workspace.[8]

Another important application is electronic assembly. Electronic components are usually small and require precise positioning. Pick-and-place robots can place components on boards, move

parts between stations, or feed machines with small products. In this field, accuracy and repeatability are very important because small positioning errors can affect the final product.[25]

Pick-and-place robots are also used in machine loading and unloading. In this case, the robot takes a part from a conveyor or tray and places it inside a machine such as a CNC machine, press, or inspection system. After the operation is completed, the robot removes the part and transfers it to another location. This reduces manual intervention and improves production continuity.

In logistics and sorting systems, robots are used to move products from one conveyor to another, sort objects according to size or destination, and prepare orders. These systems may use vision sensors or barcode readers to identify objects before placing them in the correct location. This makes the operation faster and more organized.[26]

Pick-and-place robots are also useful in photovoltaic panel manufacturing. Solar cells and photovoltaic strings are fragile components that must be handled carefully. A robotic system equipped with a suitable vacuum gripper can move these components with reduced mechanical stress and place them accurately inside the panel frame. This application is close to the work developed in this thesis, where an ABB robotic arm is used to handle photovoltaic strings in a simulated workstation.[27]

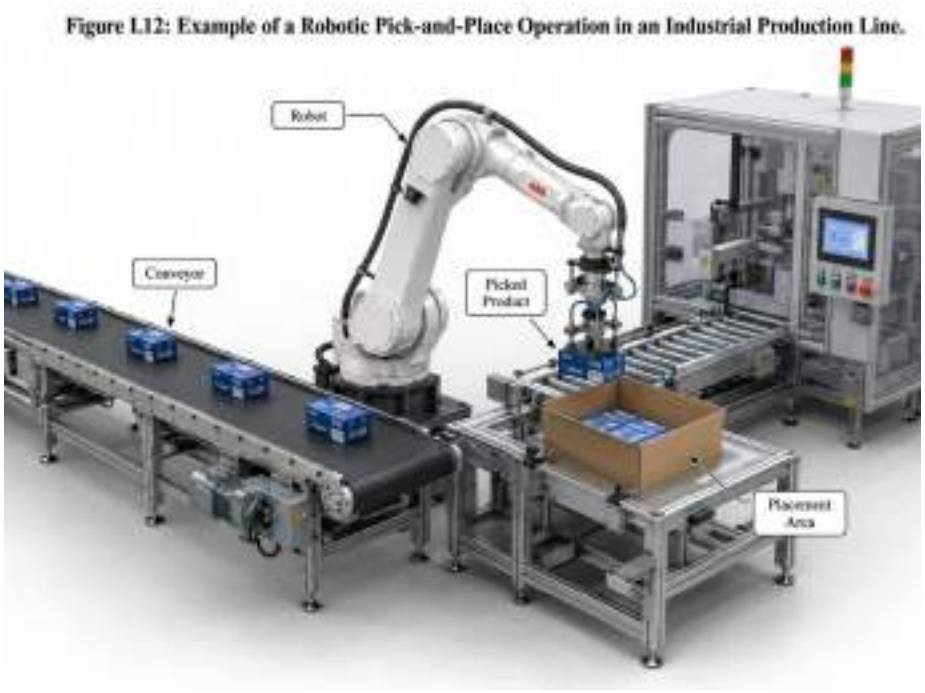


Figure I.12: Example of a robotic pick-and-place operation in an industrial production line.[27]

In general, the success of a pick-and-place application depends on the correct selection of the robot, gripper, sensors, and workstation layout. When these elements are well integrated, the system can improve productivity, reduce handling errors, and maintain a stable production flow.[27]

I.6 Conclusion

This chapter presented the general background related to industrial robotics and pick-and-place systems. First, industrial automation was introduced as an important solution for improving productivity, repeatability, safety, and production quality. Then, industrial robots were discussed through their definition, development, main classifications, and essential components.

The chapter also showed that the performance of an industrial robot depends on several elements, such as the manipulator structure, actuators, sensors, controller, and end-effector. These elements must work together correctly in order to obtain accurate and reliable robot motion.

After that, the chapter focused on pick-and-place systems. This type of robotic application is widely used in industry because it allows objects to be transferred from one position to another with speed and precision. The main components of a pick-and-place system were presented, including the robotic arm, gripper, sensors, controller, conveyor, and safety devices. The advantages, limitations, and technical challenges of these systems were also discussed.

In the context of this thesis, the pick-and-place operation is applied to the handling of photovoltaic strings. Since these components are fragile and require accurate positioning, the choice of the robot, the gripper, and the control strategy becomes very important. For this reason, the next chapter focuses on ABB robotic systems, RAPID programming, RobotStudio software, and the adaptive control principles used to develop the proposed robotic application.

Chapter II:

Design and Simulation of the Proposed Pick-and-Place System

II.1 Introduction

After presenting the theoretical background of industrial robotics and the ABB robotic environment, this chapter focuses on the practical part of the thesis. The aim is to design and simulate an automated pick-and-place system using an ABB robotic arm. The proposed system is applied to the handling of photovoltaic strings and their placement inside solar panel frames.

Photovoltaic panel manufacturing requires careful handling because solar cells and photovoltaic strings are fragile components. Incorrect manipulation may cause cracks, misalignment, or damage that can reduce the quality of the final panel. For this reason, robotic handling can be useful, especially when the task is repetitive and requires stable positioning.

The proposed robotic cell is composed of an ABB industrial robot, a conveyor system, a vacuum-based end-effector, a photovoltaic frame positioning station, and a temporary buffer area. The conveyor brings photovoltaic strings to the pickup position. The robot then picks each string and places it inside the frame. When the frame is not available, the robot transfers the string to the buffer area until the assembly operation can continue.

The practical work is developed and validated using ABB RobotStudio. This software allows the robotic cell to be modeled in a virtual environment before real implementation. Through simulation, it becomes possible to verify robot reachability, trajectory feasibility, workspace organization, and collision-free operation. RAPID programming is also used to define the robot movements, gripper control, and adaptive operating sequence.

This chapter first presents the system requirements and the general description of the proposed workstation. Then, it explains the robot selection, end-effector choice, workspace layout, adaptive control logic, and RAPID program implementation. Finally, the simulation and validation of the robotic cell are discussed.

II.2 System Description and Requirements

The proposed system is an automated robotic workstation designed to perform pick-and-place operations for photovoltaic strings. The main task of the robot is to pick photovoltaic strings from a conveyor and place them accurately inside a solar panel frame. The workstation also includes a temporary buffer area, which is used when the frame is not available or when the production flow becomes temporarily unbalanced.

The system is designed around the ABB IRB 2600 robotic arm. This robot is selected because it provides suitable reach, payload, repeatability, and compatibility with RobotStudio simulation. The robot is equipped with a vacuum-based end-effector in order to handle photovoltaic strings with reduced mechanical contact. This choice is important because photovoltaic strings are fragile and must be manipulated carefully.[2]

The proposed workstation contains four main zones:

- the conveyor zone, where photovoltaic strings arrive;
- the robot operating zone, where the robot performs the pick-and-place movements;
- the frame assembly zone, where strings are placed inside the solar panel frame;
- the buffer zone, where strings are stored temporarily when direct placement is not possible.

II.2.1 Description of the Proposed Workstation

The robotic workstation is organized to ensure smooth material flow and efficient robot movement. The conveyor is responsible for transporting photovoltaic strings toward the pickup position. Once a string reaches the pickup area, the robot moves toward it and activates the vacuum gripper. After gripping the string, the robot either places it directly into the solar panel frame or transfers it to the buffer area, depending on the state of the workstation.

The solar panel frame is placed in a fixed assembly position inside the robot workspace. The robot must place the strings one by one into the frame with correct alignment. In this work, each frame is considered to receive a defined number of photovoltaic strings according to the assembly sequence.

The buffer area is added to improve system flexibility. It allows the robot to continue handling incoming strings even when the frame is not ready. Without the buffer, the robot would stop or the conveyor would become blocked. With the buffer, the system can continue operating for a limited period and then resume direct assembly when the frame becomes available again.

This organization gives the robotic cell a more adaptive behavior. Instead of following only one fixed movement sequence, the robot chooses the appropriate action according to the availability of the frame and the state of the buffer.[14]

II.2.2 Functional Requirements

Functional requirements describe what the system must do during operation. In the proposed application, the system must automate the handling and placement of photovoltaic strings while maintaining safe and stable operation.

The main functional requirements are:

- detect the arrival of a photovoltaic string at the pickup position;
- move the robot safely toward the pickup point;
- activate the vacuum gripper and pick the string without damaging it;
- transfer the string to the solar panel frame when the frame is available;
- place the string accurately in its required position;
- transfer the string to the buffer area when the frame is not available;
- retrieve stored strings from the buffer when needed;
- repeat the cycle until the frame is completed;
- avoid collisions between the robot, gripper, conveyor, frame, and buffer;
- return the robot to a safe home position when the cycle is finished or when no object is available.

These functions must be executed in a coordinated way. The robot must not move randomly or independently from the rest of the workstation. It must react to sensor signals and follow the programmed sequence.[3]

II.2.3 Technical Requirements

Technical requirements define the hardware and software conditions needed to implement the system. They are related to the robot, end-effector, simulation environment, programming language, and workstation equipment.

The robotic system requires an ABB industrial robot with enough reach to cover the conveyor, frame, and buffer positions. It also requires sufficient payload capacity to carry both the vacuum gripper and the photovoltaic string. The robot must provide good repeatability because the placement task requires precise positioning.[9]

The selected end-effector must be lightweight and suitable for fragile flat objects. A vacuum gripper is preferred because it can hold photovoltaic strings with less direct mechanical pressure

than a mechanical gripper. The gripper must also be controlled by digital output signals from the robot controller.

The software requirements include RobotStudio for modeling, simulation, and validation of the robotic cell. RAPID programming is required to define the robot movements, tool data, work objects, gripper commands, and adaptive operating logic.[12]

The workstation also requires sensors or simulated signals to represent:

- object presence on the conveyor;
- frame availability;
- buffer availability;
- vacuum gripping confirmation;
- emergency stop or safety condition.

These signals allow the robot to select the correct operation during the pick-and-place cycle.[14]

II.2.4 Safety Requirements

Safety is an essential requirement in the design of the robotic workstation. The robot operates inside a defined working envelope and may move with high speed. For this reason, the operator must be protected from accidental contact with the robot during automatic operation.

The workstation must include a clearly defined robot operating zone. This zone should be separated from the operator area by safety barriers or equivalent protective devices. Emergency stop devices must also be available to stop the system quickly in case of abnormal operation.

The robot program must avoid unsafe movements. This means that trajectories should be checked to prevent collision with the conveyor, the frame, the buffer table, and other objects in the cell. In RobotStudio, collision detection can be used before real implementation to identify dangerous paths and correct them.[16]

Safety requirements can be summarized as follows:

- define restricted robot operating zones;
- keep operators outside the robot workspace during automatic operation;
- include emergency stop functionality;
- validate collision-free trajectories in simulation;
- avoid excessive speed near pickup and placement points;

- ensure stable gripping before moving the object;
- return the robot to a safe position when no operation is required.

These safety conditions are necessary to make the proposed robotic cell reliable and suitable for future physical implementation.[18]

II.3 Robot Selection

Robot selection is one of the most important steps in the design of the proposed pick-and-place system. The robot is the main element responsible for moving photovoltaic strings from the conveyor to the solar panel frame or to the buffer area. For this reason, the selected robot must be able to cover the complete workstation, carry the required load, and perform the movement with good repeatability.

In this work, the ABB IRB 2600 is selected as the robotic arm used in the proposed system. This robot is suitable for medium-payload industrial applications and provides a good balance between reach, precision, speed, and compact design. It is also compatible with ABB RobotStudio, which makes it possible to simulate the complete workstation before real implementation.[3]



Figure II.1: ABB IRB 2600 robot used in the proposed workstation.

II.3.1 Selection Criteria

The robot was selected according to several technical and operational criteria. These criteria are related to the nature of the handled object, the workstation layout, and the expected performance of the pick-and-place task.

The first criterion is payload capacity. The robot must be able to carry the vacuum gripper and the photovoltaic string without exceeding its maximum payload. This point is important because exceeding the payload limit can reduce positioning accuracy, increase mechanical stress, and affect the safety of the system. Even if the photovoltaic string is relatively light, the end-effector weight must also be considered.[9]

The second criterion is working reach. The robot must be able to reach all important zones of the workstation, including the conveyor pickup point, the frame assembly area, and the buffer table. If the reach is not sufficient, the robot may require an additional linear axis or a different workstation layout. The ABB IRB 2600 provides a reach suitable for a compact robotic cell.

The third criterion is repeatability. The placement of photovoltaic strings requires good positioning stability. The robot must be able to repeat the same movement several times with small variation. Good repeatability helps maintain correct string alignment inside the solar panel frame.

The fourth criterion is speed and cycle time. In industrial production, the robot must complete the operation in an acceptable time. However, speed must not be increased in a way that causes vibration or unstable handling. The selected robot must therefore provide both fast movement and controlled motion.[17]

The fifth criterion is compatibility with simulation and programming tools. Since the project is developed in RobotStudio, the selected robot must be available in the ABB robot library and compatible with RAPID programming. This allows the workstation to be modeled, programmed, and validated virtually.

The last criterion is industrial reliability. The robot must be suitable for continuous operation in a production environment. It should support industrial mounting configurations and safety integration with the rest of the workstation.[9]

II.3.2 ABB IRB 2600 Specifications

The ABB IRB 2600 is a six-axis articulated industrial robot. It is designed for applications that require high performance in a relatively compact workspace. Different versions of this robot are available, depending on payload and reach.

The main specifications of the selected robot are summarized in Table II.1.

Table II.1: Main specifications of the ABB IRB 2600.

Parameter	Specification
Robot model	ABB IRB 2600
Robot type	Six-axis articulated industrial robot
Number of axes	6
Maximum payload	Up to 20 kg depending on version
Maximum reach	Up to about 1.85 m depending on version
Main applications	Handling, assembly, machine tending, welding, pick-and-place
Mounting options	Floor, wall, shelf, tilted, or inverted mounting
Programming language	RAPID
Simulation software	ABB RobotStudio

The robot's six-axis configuration provides good flexibility, which is useful when the tool must approach different positions with controlled orientation. This is important in the proposed application because the vacuum gripper must remain correctly aligned with the photovoltaic string during picking and placement.

The available payload capacity is enough for the proposed handling task if the gripper is selected carefully. The total mass of the vacuum tool and photovoltaic string must remain lower than the payload capacity of the selected robot version. This point must be verified during the practical design stage.

The working reach allows the robot to access the conveyor, frame, and buffer area when the workstation is arranged correctly. For this reason, the robot base must be positioned in a central location that reduces travel distance and avoids unnecessary axis movements.

II.3.3 Justification of Robot Selection

The ABB IRB 2600 was selected because it satisfies the main requirements of the proposed robotic cell. It offers a suitable reach for the planned workstation and can cover the different operating zones without requiring an additional external axis. Its articulated structure also provides flexible motion, which is useful for pick-and-place tasks where the robot must move between several positions.

The robot also provides good repeatability, which is necessary for accurate placement of photovoltaic strings inside the solar panel frame. Since these components must be aligned

correctly, repeated positioning errors must be minimized. The IRB 2600 is therefore appropriate for this kind of handling operation.

Another reason for selecting this robot is its compatibility with ABB RobotStudio. This allows the complete cell to be built and tested virtually. The robot paths, target points, gripper actions, and adaptive sequence can be checked before moving to a real system. This reduces the risk of errors during implementation.

In addition, the robot can be programmed using RAPID, which supports motion instructions, input/output control, waiting conditions, and structured routines. These functions are necessary for implementing the pick-and-place sequence and the adaptive buffer logic used in this project.

For these reasons, the ABB IRB 2600 represents a suitable choice for the proposed automated pick-and-place system. It provides the required flexibility, reach, accuracy, and software compatibility for handling photovoltaic strings in a simulated industrial workstation.

II.4 End-Effector Selection and Design

The end-effector is the tool mounted at the wrist of the robot. It represents the direct contact point between the robot and the handled object. In a pick-and-place system, the end-effector is responsible for gripping, holding, transporting, and releasing the object at the correct position. For this reason, its selection has a strong influence on the reliability and safety of the whole operation.

In the proposed system, the handled objects are photovoltaic strings. These components are fragile and must be handled carefully to avoid cracks, deformation, or misalignment. A mechanical gripping system may apply direct pressure on the string, which can increase the risk of damage. For this reason, a vacuum-based end-effector is selected as the most suitable solution.



Figure II.2: Vacuum end-effector used for handling flat fragile components.

II.4.1 Gripper Types

Several gripper types are used in robotic handling applications. The choice depends on the object material, shape, weight, surface condition, and required handling accuracy.

Mechanical grippers use fingers or jaws to hold the object. They are suitable for rigid parts with regular shapes. Their main advantage is strong gripping force and stable holding. However, they may not be suitable for fragile photovoltaic strings because the contact force can damage the object if it is not well controlled.

Vacuum grippers use suction cups and vacuum pressure to hold the object. They are commonly used for flat or smooth surfaces, such as sheets, glass, boxes, panels, and photovoltaic components. Their advantage is that they reduce direct mechanical pressure on the object. This makes them suitable for delicate handling operations.

Magnetic grippers are used to handle ferromagnetic materials. They are simple and fast, but their use is limited to metallic objects. Since photovoltaic strings are not magnetic, this solution is not suitable for the proposed system.

Adaptive grippers can adjust their shape according to the object geometry. They are useful when the system handles different types of objects. However, they are usually more complex and may not be necessary when the handled object has a regular flat shape.

Based on this comparison, the vacuum gripper is the most appropriate choice for the photovoltaic string handling task.

II.4.2 Vacuum Gripper Selection

The selected end-effector is based on a vacuum gripping principle. It uses suction cups connected to a vacuum source. When the robot reaches the pickup point, the vacuum is activated and the cups hold the photovoltaic string. After the robot reaches the placement position, the vacuum is deactivated and the string is released.

This solution is suitable for the proposed application because photovoltaic strings are relatively flat and require gentle handling. Vacuum gripping distributes the holding force over several contact points, which reduces the risk of local stress on the object. It also allows fast gripping and releasing, which is useful for repetitive pick-and-place operations.

The vacuum gripper must be lightweight in order to avoid exceeding the payload capacity of the ABB IRB 2600. The total carried load includes the gripper, suction cups, fittings, possible frame structure, and the photovoltaic string. Therefore, the tool weight must be checked carefully during the design stage.

II.4.3 Technical Characteristics

The technical characteristics required for the selected vacuum end-effector are summarized in Table II.2.

Table II.2: Required characteristics of the vacuum end-effector.

Characteristic	**Requirement**
Gripping principle	Vacuum suction
Object type	Photovoltaic string
Object condition	Fragile and flat component
Tool structure	Lightweight and rigid
Contact elements	Multiple suction cups
Control method	Digital output signal
Main objective	Stable handling with reduced mechanical stress
Compatibility	ABB IRB 2600 and RobotStudio simulation

The gripper should contain several suction cups distributed along the photovoltaic string. This distribution helps maintain the object in a stable position during motion. It also reduces bending and vibration while the robot transfers the string from one position to another.

The tool center point must be defined correctly in RobotStudio. This is important because the robot movements are calculated according to the tool center point. If the tool data is not correct, the robot may place the string with an offset or wrong orientation.

The vacuum control can be represented in the RAPID program using digital output instructions. For example, the output is activated when the robot reaches the pickup point and deactivated after the string is placed in the frame or buffer area.

II.4.4 Suitability for Photovoltaic String Handling

The vacuum-based end-effector is suitable for photovoltaic string handling for several reasons. First, it limits direct mechanical force on the object. This is important because photovoltaic strings are sensitive and may be damaged by excessive pressure.

Second, the use of multiple suction cups improves stability. The object is not held from only one point, but from several positions along its surface. This reduces the risk of rotation, slipping, or bending during robot motion.

Third, the vacuum gripper is easy to control in a robotic program. It can be activated and deactivated using simple digital output signals. This makes it compatible with the adaptive sequence used in this thesis, where the robot may place the string either in the frame or in the buffer area.

Finally, this type of end-effector is suitable for simulation in RobotStudio. The tool can be represented as a simplified 3D model, and its activation can be included in the RAPID program. This allows the complete pick-and-place sequence to be tested virtually before real implementation.

For these reasons, the vacuum gripper is selected as the most appropriate end-effector for the proposed ABB robotic pick-and-place system.

II.5 Workspace and Cell Layout

The workspace and cell layout represent an important part of the proposed robotic system. A good layout allows the robot to reach all required positions with short and safe movements. It also helps reduce cycle time, avoid collisions, and improve the general flow of the production process.

In this work, the robotic cell is designed around the ABB IRB 2600 robot. The workstation includes a conveyor for photovoltaic strings, a solar panel frame positioning area, a temporary buffer area, and the robot operating zone. All these elements must be placed inside the reachable workspace of the robot.

II.5.1 Workstation Design

The workstation is designed to support the complete pick-and-place sequence. The conveyor brings photovoltaic strings to the pickup position. The robot picks the string using the vacuum end-effector, then places it either in the solar panel frame or in the temporary buffer area.

The robot is positioned near the center of the main working zones. This position allows it to reach the conveyor, the frame, and the buffer without excessive movement. A central robot position also helps reduce unnecessary axis rotation and makes the robot paths easier to optimize.

The main elements of the workstation are:

- ABB IRB 2600 robotic arm;
- input conveyor for photovoltaic strings;
- vacuum-based end-effector;
- solar panel frame positioning station;
- temporary buffer area;
- safety zone around the robot workspace.

The workstation must be arranged in a way that keeps the robot movement logical and safe. The pickup and placement points should be close enough to reduce travel distance, but not too close to create collision risks. The buffer area should also be placed in a reachable position that does not block access to the frame or conveyor.

II.5.2 Conveyor and Object Positioning

The conveyor is used to transport photovoltaic strings toward the robot pickup position. Its position must be carefully selected because it affects robot reachability and cycle time. If the conveyor is too far, the robot may not reach the object correctly. If it is too close, the robot may have limited motion or collision risk.

The pickup position is defined at the end of the conveyor or at a fixed detection point. When the string reaches this point, the robot can move to the pickup target and activate the vacuum gripper. In the simulation, this position is represented by a predefined robot target.

Good object positioning is necessary because the vacuum gripper must be aligned with the photovoltaic string before activation. A wrong position may cause weak gripping, unstable motion, or object misplacement. For this reason, the object must arrive in a controlled orientation on the conveyor.

In a real system, sensors can be used to confirm the presence of the photovoltaic string at the pickup position. In RobotStudio, these signals can be simulated or represented in the RAPID program using digital inputs.

II.5.3 Frame Positioning Station

The frame positioning station is the area where the photovoltaic strings are placed during the assembly process. The solar panel frame must be fixed in a stable position to ensure accurate placement. If the frame moves or is not aligned correctly, the robot may place the strings with positioning errors.

The frame must be located inside the robot's working envelope and at a comfortable distance from the robot base. This allows the robot to place the strings without excessive joint movement. The target positions inside the frame are defined according to the required arrangement of the photovoltaic strings.

In this work, the robot places the strings sequentially inside the frame. Each placement point must be defined as a separate target in RobotStudio. This allows the robot to follow a clear sequence and place every string in its correct location.

II.5.4 Buffer Area Design

The buffer area is used as a temporary storage zone for photovoltaic strings. Its role is to improve production continuity when the frame is not available. Instead of stopping the robot or blocking the conveyor, the robot can place the incoming string in the buffer and retrieve it later.

The buffer must be placed inside the robot workspace and should be easy to access. It should not interfere with the robot path between the conveyor and the frame. The buffer positions must be organized clearly so that the robot can store and retrieve strings without confusion.

Each buffer position can be represented by a predefined robot target. When the frame is unavailable, the robot selects an empty buffer position and places the string there. When the frame becomes available again, the robot retrieves the stored string and places it in the frame.

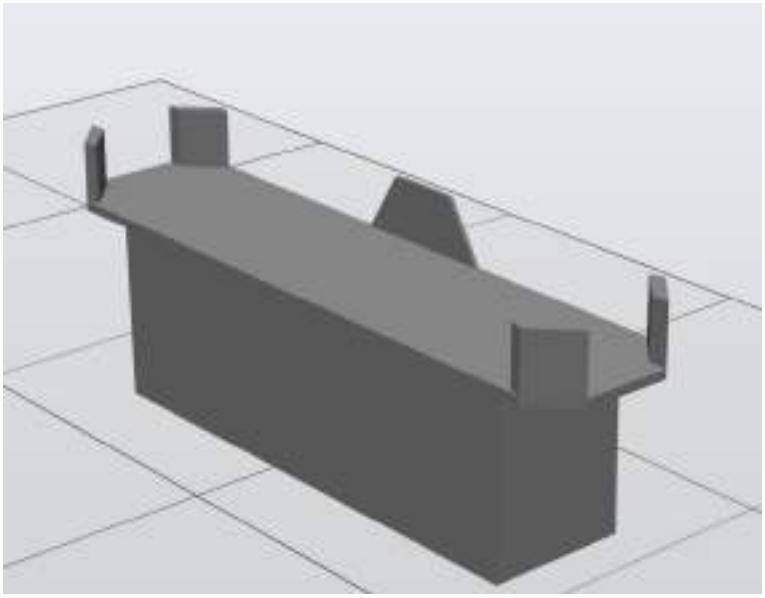


Figure II.3: Temporary buffer area used for adaptive operation.

The buffer area gives the system a more flexible behavior. It allows the robot to adapt to temporary changes in the production flow and reduces unnecessary waiting time.

II.5.5 Safety Zones

Safety zones are necessary in any industrial robotic cell. Since the robot can move with high speed and force, the operator must be protected from entering the robot workspace during automatic operation.

The main safety zones in the proposed workstation are:

- robot operating zone;
- conveyor movement zone;
- frame assembly zone;
- buffer area;
- operator safety zone.

The robot operating zone includes all areas that the robot can reach during movement. This zone should be restricted during automatic operation. The conveyor zone must also be considered because moving parts may create additional risks. The operator safety zone should

be separated from the robot movement area and used only for supervision, maintenance, or manual intervention when the system is stopped.[19]

In RobotStudio, safety validation can be supported by checking robot paths and detecting possible collisions. This helps ensure that the robot does not hit the conveyor, frame, buffer, or other objects during simulation.

The correct organization of the workspace is therefore essential for both performance and safety. It allows the robot to complete the pick-and-place task efficiently while reducing the risk of collision and improving the reliability of the proposed system.[19]

II.6 Control Logic and Adaptive Operating Strategy

The control logic represents the link between the physical workstation and the robot program. In the proposed pick-and-place system, the robot does not execute only one fixed sequence. It must choose the suitable action according to the current state of the conveyor, the solar panel frame, and the temporary buffer area.

At the design level, the adaptive strategy is based on a simple principle. When a photovoltaic string is present on the conveyor and the frame is ready, the robot performs direct placement. When the frame is not available, the robot uses the buffer area to store the incoming string temporarily. When the frame becomes available again and a stored string exists in the buffer, the robot can retrieve it and place it in the frame.

This strategy avoids unnecessary waiting and gives the workstation more flexibility. It also keeps the design close to real industrial practice, where upstream and downstream stations do not always work at exactly the same rhythm. The buffer therefore acts as an intermediate zone that helps absorb temporary interruptions in the production flow.

In this chapter, the control logic is presented only at the system design level. The detailed implementation using station logic, sensor expressions, digital input signals, and RAPID procedures is developed in Chapter III. This separation avoids repeating the same explanation and keeps Chapter III focused on the design of the proposed robotic cell.

II.6.1 General Pick-and-Place Sequence

The basic operating sequence starts when a photovoltaic string reaches the pickup position on the conveyor. The robot moves from its home or standby position toward an approach point

located above the conveyor. It then moves down to the pickup target, activates the vacuum gripper, and lifts the string safely before moving toward the selected destination.

If the frame is available, the selected destination is the frame station. The robot places the string in the required location, releases the vacuum, and returns to a safe position or prepares for the next cycle. If the frame is not available, the robot uses the buffer area instead of stopping the cycle completely.

II.6.2 Adaptive Operating Principle

The adaptive operating principle depends on three main workstation states: string availability, frame availability, and buffer state. These conditions are checked before each handling operation. Based on them, the system selects one of the possible actions: direct placement, buffer storage, buffer retrieval, or waiting in a safe position.

The objective is not to develop a complex dynamic controller at this stage, but to build a practical decision-based control strategy. This approach is suitable for simulation and can later be expanded with real sensors, PLC communication, machine vision, or conveyor tracking.

II.6.3 System Flowchart

The system flowchart summarizes the global sequence of the adaptive strategy. It begins with initialization, then checks whether a string is present on the conveyor. If a string exists, the system checks whether the frame is available. If the frame is ready, the robot performs direct placement. If the frame is not ready, the robot checks the buffer state and stores the string if a free position is available.

When no string is present on the conveyor, the system checks whether the frame is available and whether the buffer contains stored strings. If this condition is satisfied, the robot performs a buffer recovery operation. If no valid condition is available, the robot waits or returns to a safe home position.

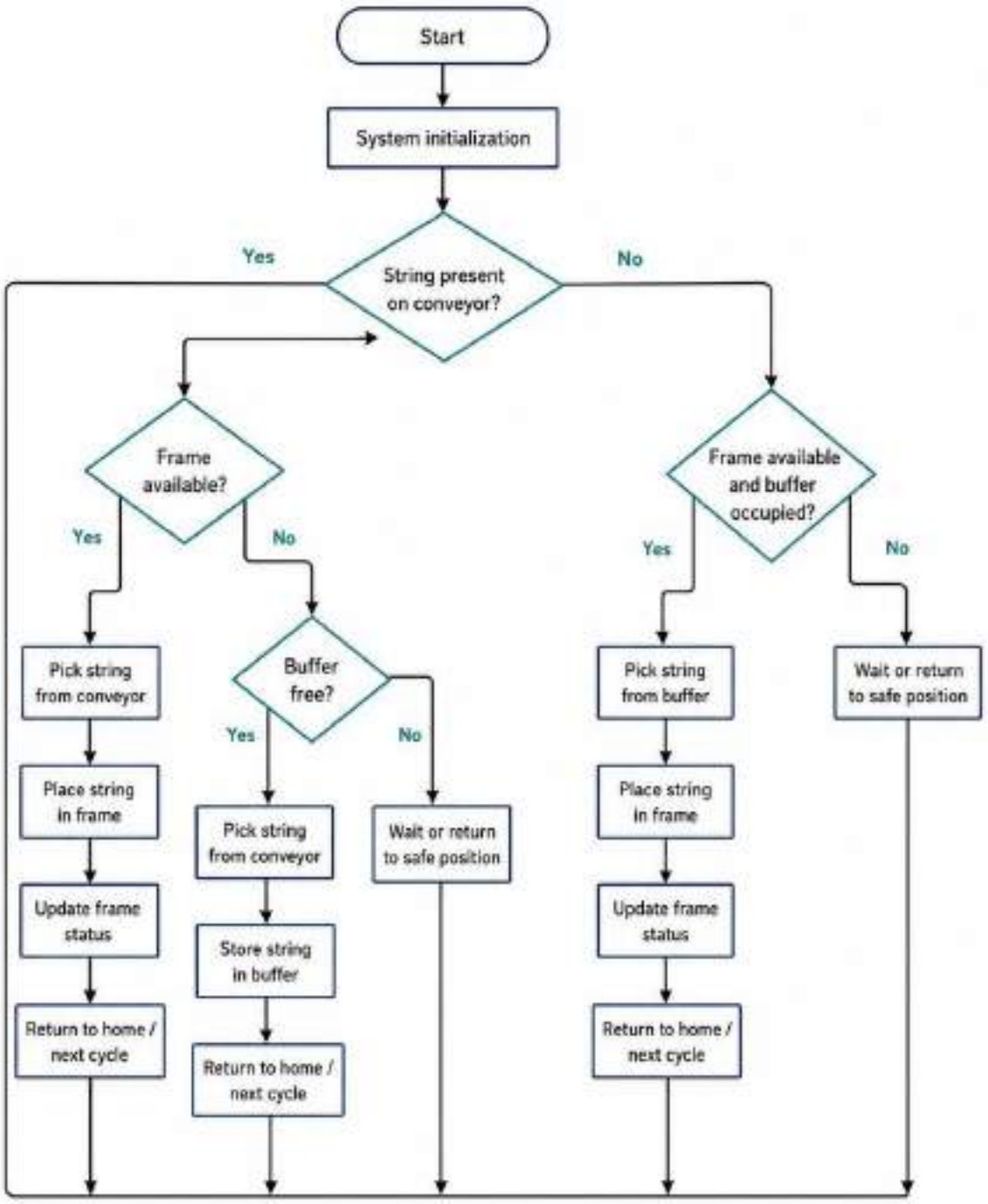


Figure II.4: Flowchart of the proposed adaptive pick-and-place strategy.

II.7 RAPID Program Implementation

RAPID programming is used to translate the proposed operating logic into executable robot instructions. In the design stage, the program is considered as a structured set of movements, input/output actions, and decision conditions. The final detailed program architecture is presented in Chapter IV, while this section gives only the general organization required for the proposed pick-and-place task.

The program must control the robot motion, activate and deactivate the vacuum gripper, read the required input conditions, and select the appropriate operation. To keep the program clear, the task is divided into separate routines instead of writing the complete process in one long sequence.

II.7.1 Program Organization

The proposed RAPID program is organized around a main routine and several operational routines. The main routine is responsible for initialization and general supervislion. The operational routines are used for picking from the conveyor, placing in the frame, storing in the buffer, and retrieving from the buffer.

This modular structure makes the program easier to read and modify. For example, if the buffer position changes, only the buffer routine needs to be adjusted. Similalrly, if the gripper control is modified, the corresponding pickup and release instructions can be updated without rewriting the complete program.

II.7.2 Motion and Gripper Control

The robot movements are based mainly on joint and linear motions. Joint movements are useful for fast travel between distant areas, while linear movements are preferred near pickup and placement points because they give better control of the tool path. The vacuum gripper is controlled using digital output instructions, with short waiting times added to ensure stable gripping and releasing.

The RAPID implementation also requires correct definition of the tool data and work objects. The tool data represents the vacuum end-effector mounted on the robot wrist, while work objects can be used to define coordinate references for the conveyor, frame station, and buffer area.

II.7.3 Synchronization with the Workstation

Synchronization is necessary because the robot must not act independently from the workstation. It should pick a string only when material is available, and it should place the string only when the selected destination is ready. In the practical implementation, this synchronization is achieved using digital inputs generated from the station logic.

The detailed relation between sensor states, logic expressions, digital input commands, and RAPID procedures is presented in Chapter III. This makes Chapter IV the implementation chapter, while the present section remains an overview of the programming approach.

II.8 RobotStudio Simulation and Validation

RobotStudio simulation is used to verify the feasibility of the proposed robotic cell before real implementation. The main purpose of this stage is to check whether the ABB IRB 2600 can reach the required positions, execute the planned paths, avoid collisions, and perform the pick-and-place sequence correctly inside the virtual workstation.

The simulation environment includes the robot, conveyor, frame station, buffer area, and vacuum end-effector. It also allows the user to define targets, test movements, and observe the robot behavior under different operating conditions. The detailed simulation execution and results are presented in Chapter III.

II.8.1 Cell Modeling

The robotic cell is first modeled by placing the main components inside the RobotStudio station. The robot is positioned so that the conveyor, frame station, and buffer area remain inside its reachable workspace. This arrangement helps reduce unnecessary robot motion and improves the overall organization of the workstation.

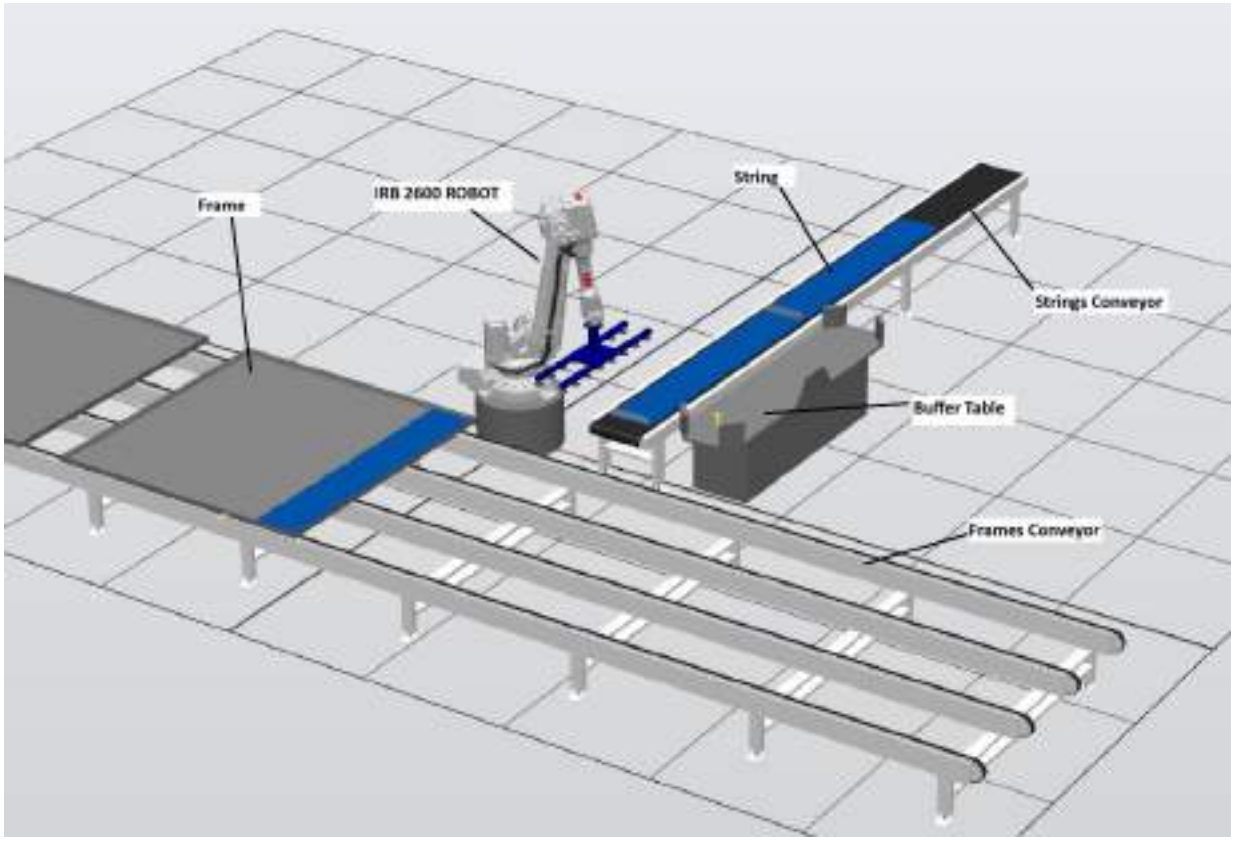


Figure II.5: RobotStudio simulation of the proposed robotic pick-and-place cell.

II.8.2 Path Planning and Validation

Path planning consists of defining the targets and motion sequence required for the robot to move between the different workstations. Approach and departure points are added near the conveyor, frame, and buffer to reduce the risk of collision and to make the motion smoother.

The planned paths are validated by checking reachability, tool orientation, and possible interference with surrounding components. In this way, the simulation helps identify layout or programming problems before moving toward physical implementation.

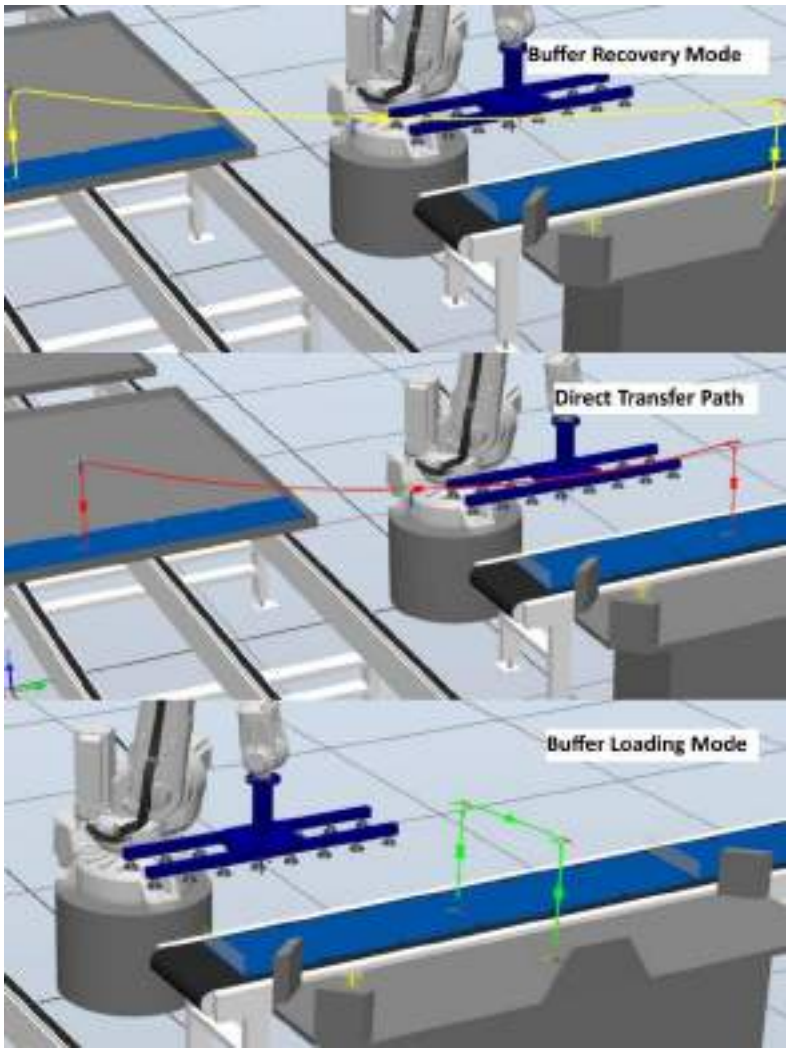


Figure II.6: Robot path planning for the pick-and-place operation.

II.8.3 Collision and Reachability Checking

Collision checking is performed to ensure that the robot, end-effector, handled string, conveyor, frame station, and buffer area do not interfere during movement. Reachability verification confirms that all required targets are accessible from the selected robot base position.

These validation steps are important because they determine whether the proposed design can be considered technically feasible. They also provide useful information for improving the workstation layout and adjusting the robot trajectories.

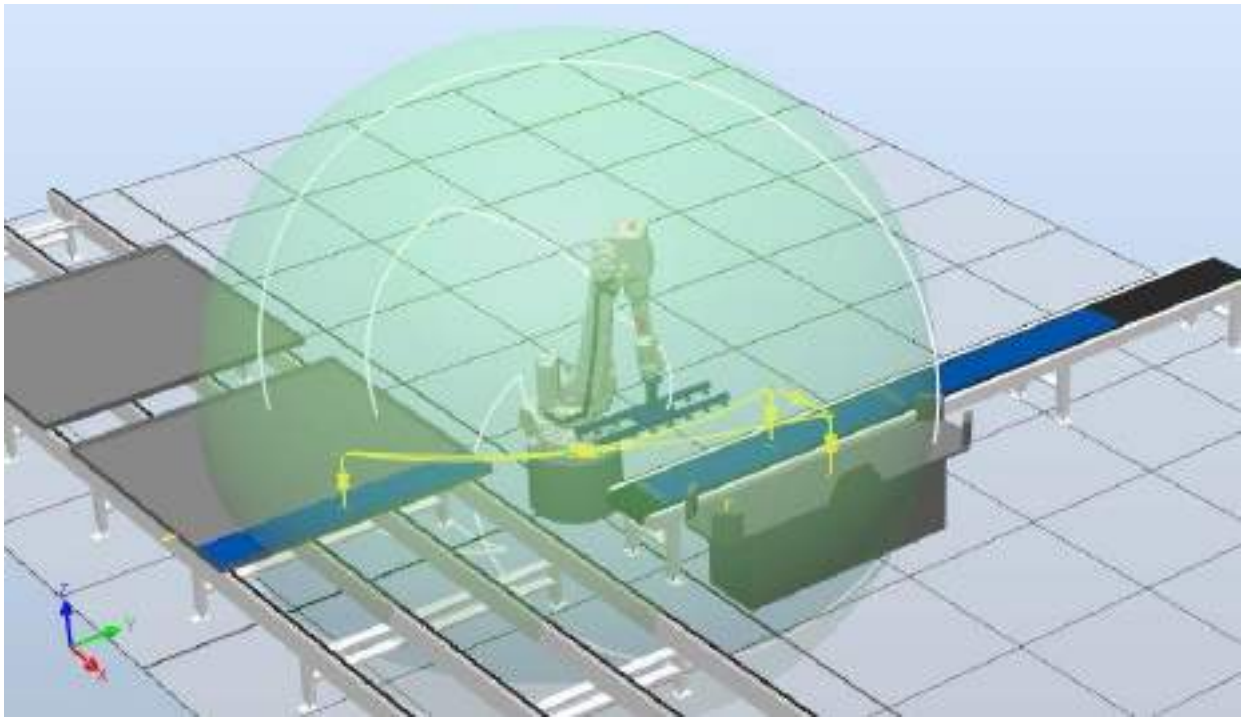


Figure II.7: Reachability verification of the robot inside the proposed workstation.

II.9 Conclusion

This chapter presented the design and simulation of the proposed ABB robotic pick-and-place system. The objective was to develop a robotic workstation capable of handling photovoltaic strings and placing them accurately inside a solar panel frame, while also using a temporary buffer area when direct placement is not possible.

First, the system requirements were defined. The proposed workstation includes a conveyor, an ABB IRB 2600 robotic arm, a vacuum-based end-effector, a frame positioning station, and a buffer area. The functional, technical, and safety requirements were described in order to clarify the expected behavior of the system.

Then, the ABB IRB 2600 was selected as the main robotic arm because it provides suitable reach, repeatability, flexibility, and compatibility with RobotStudio. A vacuum gripper was also selected because it is more appropriate for handling fragile and flat photovoltaic strings with reduced mechanical stress.

The workspace layout was organized to allow the robot to reach the conveyor, frame, and buffer positions with safe and efficient movements. The adaptive operating strategy was also explained. This strategy allows the robot to place strings directly in the frame when it is available, or to store them temporarily in the buffer when the frame is not ready.

RAPID programming was used to describe the robot movements, gripper control, and decision logic. The program was organized into routines to make the sequence easier to understand and modify. Finally, RobotStudio simulation was used to validate the proposed cell by checking reachability, path feasibility, collision-free operation, and the general behavior of the adaptive pick-and-place process.

Chapter III:

Implementation, Simulation Results, and Performance Analysis

III.1 Introduction

This chapter presents the implementation and validation of the proposed robotic pick-and-place cell in ABB RobotStudio. While the previous chapter described the general design of the workstation, this chapter focuses on the practical implementation of the operating modes, station logic, RAPID program structure, target definition, trajectory planning, and simulation results.

The implementation is based on three operating modes: direct transfer, buffer loading, and buffer recovery. These modes allow the robot to react to changes in photovoltaic string availability, frame availability, and buffer state. The use of station logic simplifies the robot program because the sensor conditions are processed before being transmitted to the robot controller.

The chapter also presents the main target points, motion instructions, speed parameters, and simulation scenarios used to test the robotic cell. Finally, the results, performance analysis, limitations, and possible future improvements are discussed.

III.2 Implemented Pick-and-Place Operating Modes

The primary objective of the developed robotic cell is the automated handling of photovoltaic strings between the input conveyor, the frame station, and the buffer area. Unlike a conventional fixed pick-and-place system, the proposed cell must react to different production situations. For this reason, three operating modes were implemented.

The main elements of the robotic workstation are summarized in Table III.1.

Table III.1: Main components of the robotic workstation.

Component	**Function**
Input conveyor	Transports photovoltaic strings to the pickup area.
ABB IRB 2600 robot	Performs the pick-and-place movements between the workstations.
Vacuum end-effector	Grips and releases photovoltaic strings with reduced mechanical stress.
Frame station	Receives photovoltaic strings during the assembly process.
Buffer area	Stores strings temporarily when direct placement is not possible.
Station logic	Processes sensor conditions and generates digital input commands.

III.2.1 Direct Transfer Mode

Direct Transfer Mode represents the normal operating condition. In this mode, photovoltaic strings are available on the input conveyor and the assembly frame is ready to receive them. The robot picks the string from the conveyor and transfers it directly to the frame station.

This mode minimizes handling time because no intermediate storage operation is required. It also reduces unnecessary robot travel and improves production throughput.

III.2.2 Buffer Loading Mode

Buffer Loading Mode is used when photovoltaic strings are available on the conveyor but the frame is not available. Instead of stopping the system, the robot picks the incoming string and places it in the buffer area.

The buffer therefore works as an intermediate storage zone. This mode helps avoid conveyor blockage and keeps the material flow active during temporary interruptions at the frame station.

III.2.3 Buffer Recovery Mode

Buffer Recovery Mode is used when the frame becomes available but no string is detected on the input conveyor. In this case, the robot retrieves a previously stored string from the buffer and transfers it to the frame station.

This operating mode reduces the effect of temporary supply interruptions and allows the system to continue the assembly process using material already stored inside the workstation.

III.3 Sensor Logic and Digital Input Generation

The operation of the robotic cell is coordinated through sensor information collected from the conveyor, the frame station, and the buffer area. These sensors do not control the robot directly. Instead, their states are processed in the station logic layer, which generates simplified digital input commands for the robot program.

This approach keeps the RAPID program clearer because the robot receives only the final command related to the selected operating mode, instead of evaluating all raw sensor signals inside the motion program.

III.3.1 Sensor Placement

The conveyor is equipped with two sensors placed at opposite ends of the conveyor area. Their purpose is to indicate whether material is present on the conveyor or whether the conveyor is empty. A third sensor is located at the frame station to detect the presence of the assembly frame. A fourth sensor monitors the buffer area and indicates whether stored material is available.

The sensor arrangement is designed to provide enough information for selecting the appropriate operating mode without making the control system too complex.

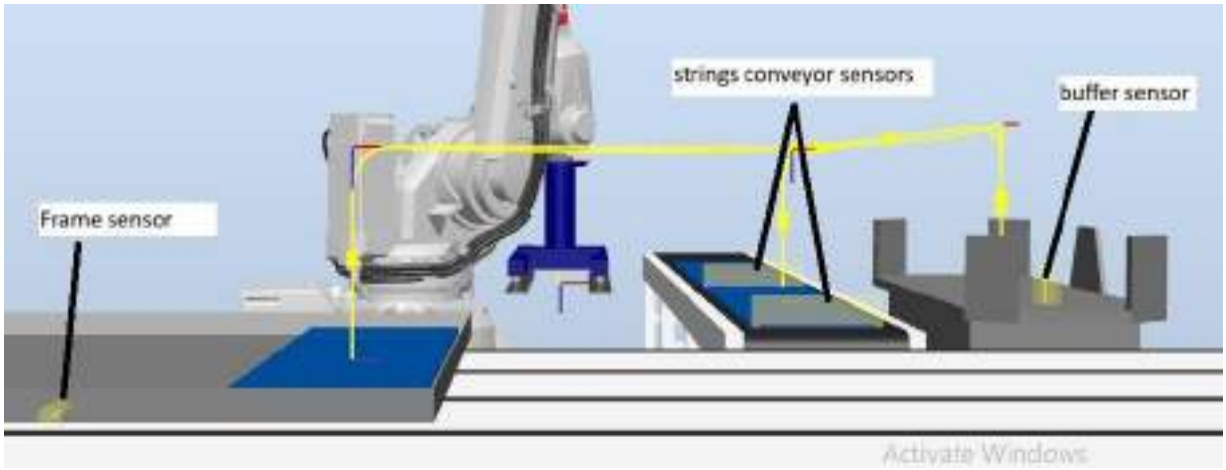


Figure III.1: Sensor positions in the proposed robotic cell.

III.3.2 Logical Expressions

The sensor states are represented by four logical variables. The frame sensor is represented by A, the first-string sensor by B, the second-string sensor by C, and the buffer sensor by D. These variables are combined to generate three digital input commands corresponding to the three operating modes.

Table III.2: Sensor logic expressions and generated digital inputs.

Logic expression	**Generated command**	**Meaning**
A AND B	DI_P10	Frame available and string available.
A AND (NOT B) AND (NOT C) AND D	DI_P20	Frame condition and buffer-related storage condition.
(NOT A) AND B	DI_P30	Alternative recovery or material availability condition.

In the final thesis, the meaning of each signal must be checked with the actual RobotStudio station logic. If the logical variables A, B, C, and D are assigned differently in the station, the expressions must be updated accordingly before submission.

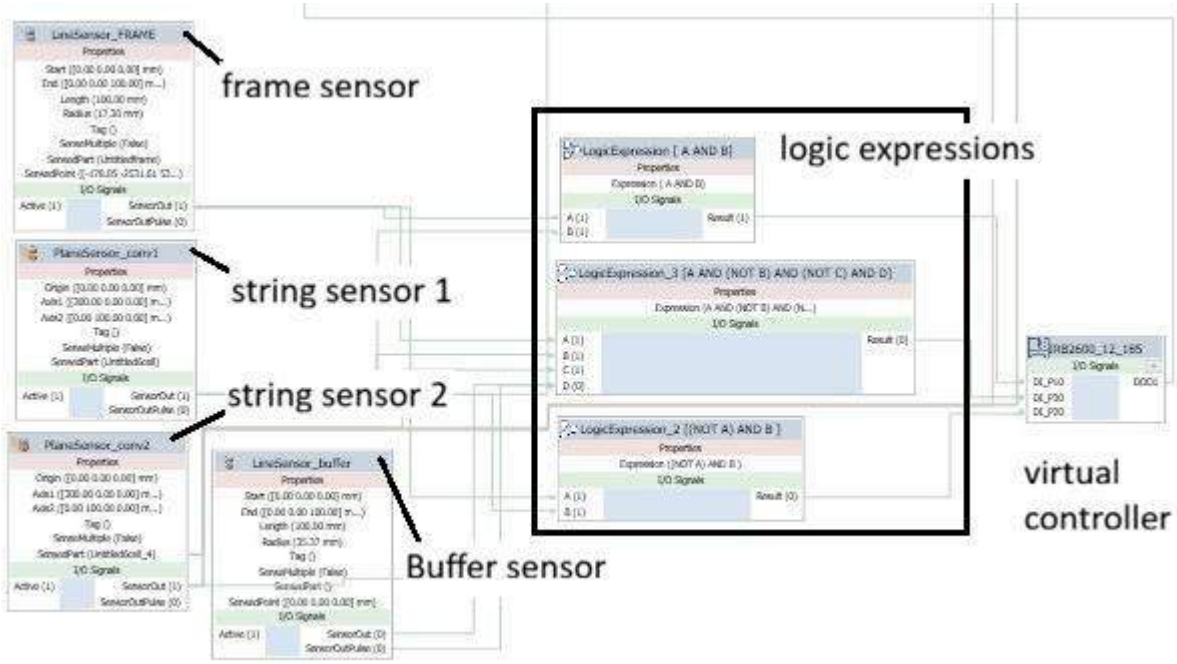


Figure III.2: Station logic functions used for digital input generation.

III.3.3 Generated Digital Inputs

The generated digital inputs are transmitted to the robot controller. Each input corresponds to one operating mode. The robot program checks these inputs and calls the appropriate RAPID procedure.

Table III.3: Digital input signals and selected operating modes.

Input signal	Production condition	Selected operation
DI_P10	Strings available and frame available	Direct Transfer Mode
DI_P20	Strings available and frame unavailable	Buffer Loading Mode
DI_P30	Strings unavailable and frame available	Buffer Recovery Mode

III.4 RAPID Program Architecture

The RAPID program is organized into three principal sections: system initialization, decision-making, and execution. This organization makes the program easier to understand and modify, especially when several operating modes are used in the same robotic cell.

III.4.1 System Initialization

The initialization section prepares the robot for automatic operation. At startup, the robot moves to a predefined home position. This position is also used as a standby position when no valid operating condition is detected.

After initialization, the program enters a continuous execution loop where the digital input signals are evaluated repeatedly.

III.4.2 Decision-Making Layer

The decision-making layer checks the digital inputs generated by the station logic. According to the active input signal, the robot selects the corresponding handling procedure. This layer separates logical decision-making from motion execution, which makes the program more structured.

```
PROC main()
    zCurrentOffset := 0;
     MoveL p10,v1000,z100,tVacuum\WObj:=wobj0;
    WHILE TRUE DO
         IF DI_P10=1 THEN
      Path_10;
    ELSEIF DI_P20=1 THEN
       Path_20;
    ELSEIF DI_P30=1 THEN
       Path_30;
    ELSE
       MoveL p10,v1000,z100,tVacuum\WObj:=wobj0;
        WaitUntil (DI_P10=1) OR (DI_P20=1) OR (DI_P30=1);
    ENDIF
    ENDWHILE
```

Figure III.3: System initialization and decision-making section of the RAPID program.

III.4.3 Execution Layer

The execution layer contains three independent procedures. Each procedure performs one complete material-transfer cycle and then returns control to the decision-making layer. This structure avoids mixing all movements in a single long sequence.

Table III.4: RAPID procedures used for each operating mode.

Operational function	RAPID procedure	Description
Direct Transfer Mode	Path_10	Transfers strings from the conveyor to the assembly frame.
Buffer Loading Mode	Path_20	Transfers strings from the conveyor to the buffer area.
Buffer Recovery Mode	Path_30	Retrieves stored strings from the buffer area and transfers them to the frame.

```
PROC Path_10()
    MoveL before_Pick_Conveyor_String,v1000,z100,tVacuum\WObj:=wobj0;
    MoveL Pick_Conveyor_String,v1000,fine,tVacuum\WObj:=wobj0;
    WaitTime 1;
    SetDO DO01,1;
    WaitTime 1;
    MoveL after_Pick_Conveyor_String,v3000,z50,tVacuum\WObj:=wobj0;
    MoveC Midway_Workstations,before_place_frame,v5000,z100,tVacuum\WObj:=wobj0;
    MoveL Place_Frame,v1000,fine,tVacuum\WObj:=wobj0;
    WaitTime 1;
    SetDO DO01,0;
    WaitTime 1;
    MoveL after_place_frame,v1000,z100,tVacuum\WObj:=wobj0;
    MoveC Midway_Workstations,before_Pick_Conveyor_String,v5000,z100,tVacuum\WObj:=wobj0;

ENDPROC
PROC Path_20()
    MoveL before_Pick_Conveyor_String,v1000,z100,tVacuum\WObj:=wobj0;
    MoveL Pick_Conveyor_String,v1000,fine,tVacuum\WObj:=wobj0;
    WaitTime 1;
    SetDO DO01,1;
    WaitTime 1;
    MoveL after_Pick_Conveyor_String,v3000,z50,tVacuum\WObj:=wobj0;
    MoveL before_PP_Buffer_String,v1000,z50,tVacuum\WObj:=wobj0;
    MoveL Offs (Pick_and_Place_Buffer_String,0,0,zCurrentOffset),v1000,fine,tVacuum\WObj:=wobj0;
    WaitTime 1;
    SetDO DO01,0;
    WaitTime 1;

    MoveL After_PP_Buffer_String,v1000,z100,tVacuum\WObj:=wobj0;
      zCurrentOffset := zCurrentOffset + 10;

ENDPROC
PROC Path_30()
     zCurrentOffset := zCurrentOffset - 10;
    MoveL before_PP_Buffer_String,v1000,z100,tVacuum\WObj:=wobj0;
    MoveL Offs(Pick_and_Place_Buffer_String,0,0,zCurrentOffset),v1000,fine,tVacuum\WObj:=wobj0;
    WaitTime 1;
    SetDO DO01,1;
    WaitTime 1;
    MoveL After_PP_Buffer_String,v3000,z50,tVacuum\WObj:=wobj0;
    MoveC Midway_Workstations,before_place_frame,v5000,z100,tVacuum\WObj:=wobj0;
    MoveL Place_Frame,v1000,fine,tVacuum\WObj:=wobj0;
    WaitTime 1;
    SetDO DO01,0;
    WaitTime 1;
    MoveL after_place_frame,v3000,z50,tVacuum\WObj:=wobj0;
    MoveC Midway_Workstations,before_PP_Buffer_String,v5000,z100,tVacuum\WObj:=wobj0;
ENDPROC
ENDMODULE
```

Figure III.4: Three main RAPID paths used in the robotic program.

III.5 Motion Strategy and Trajectory Parameters

The motion strategy was developed to ensure safe and accurate handling of photovoltaic strings while maintaining smooth transfers between workstations. Linear movements are used near pickup and placement points because accurate tool positioning is required. Circular or blended movements are used during transfer stages to improve motion continuity and reduce unnecessary stops.

Fine positioning is applied at critical interaction points, especially during gripping and releasing. Blended zones are used during intermediate movements to reduce cycle time while keeping acceptable trajectory smoothness. Dynamic offsets are also used for the buffer area so that different storage levels can be accessed from a reference target.

Table III.5: Application of motion instructions in the robotic program.

Motion element	**Application**
MoveL	Approach, pickup, placement, and departure operations.
MoveC	Smooth transfers between workstations.
fine	Precise positioning at pick and place locations.
z50 / z100	Blended transitions during intermediate movements.
v1000	Controlled handling near critical points.
v3000	Intermediate movements.
v5000	Long-distance transfer movements.
Offs()	Dynamic adjustment of buffer stack positions.

III.6 Target Point Definition in RobotStudio

The robot trajectory is defined using a set of target positions created in RobotStudio. These targets represent the key positions needed for the pick-and-place cycle, including home position, conveyor pickup position, frame placement position, buffer position, and intermediate transit points.

Targets are created using the jogging and target teaching tools available in RobotStudio. After creating each target, its position and orientation are checked through simulation to ensure correct tool alignment and safe robot motion.

Table III.6: Principal target points used in the robotic cell.

Target	Function
p10	Home position.
Pick_Conveyor_String	String pickup location.
Before_Pick_Conveyor_String	Conveyor approach position.
After_Pick_Conveyor_String	Conveyor departure position.
Place_Frame	Frame placement location.
Before_place_frame	Frame approach position.
After_place_frame	Frame departure position.
Pick_and_Place_Buffer_String	Buffer storage or retrieval position.
Before_PP_Buffer_String	Buffer approach position.
After_PP_Buffer_String	Buffer departure position.
Midway_Workstations	Intermediate transfer point.

III.7 Trajectory Optimization

Trajectory optimization was performed by adjusting the workstation layout, target positions, motion types, and zone parameters. The conveyor, buffer, and frame station were placed inside the robot working envelope to reduce excessive joint motion and avoid unreachable targets.

Circular and blended paths were introduced where possible to improve motion continuity. Fine positioning was kept at pickup and placement points because these locations require accurate interaction between the gripper and the photovoltaic string. Buffer management was improved through the use of position offsets, allowing different storage levels to be reached without creating a large number of independent targets.

A possible future improvement would be the use of conveyor tracking. This would allow the robot to pick moving strings directly from the conveyor, reducing idle time and improving production throughput.

III.8 Simulation Execution

After completing the station design, station logic, target definition, and RAPID programming, the complete system was tested in RobotStudio. The simulation was executed under the three

operating scenarios defined in the control strategy: direct transfer, buffer loading, and buffer recovery.

The objective of these tests was to verify whether the robot correctly responds to the digital commands generated by the station logic and whether each movement sequence can be completed without collision or programming errors.

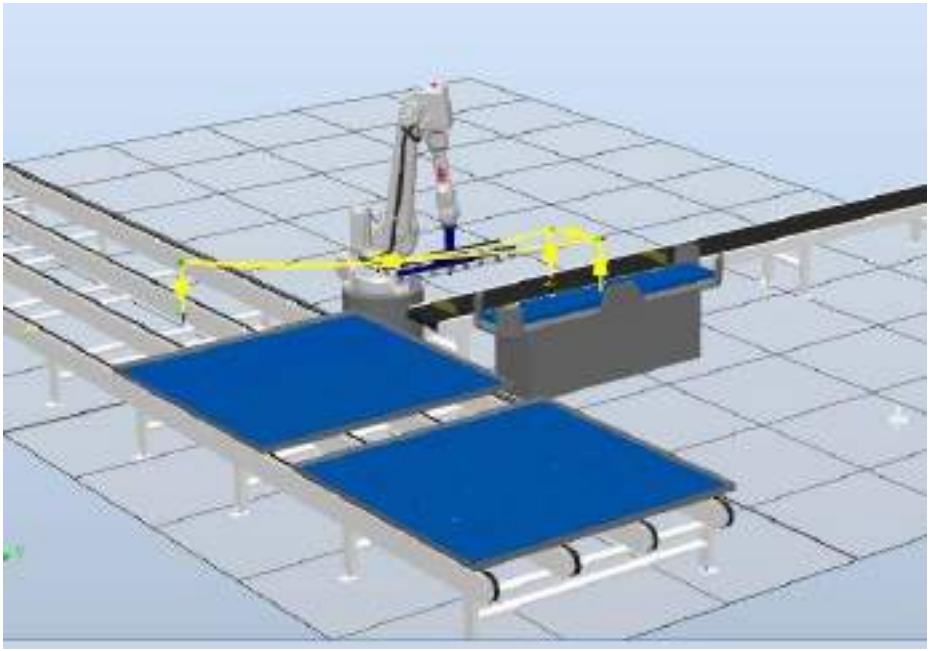


Figure III.5: Complete simulation station used in RobotStudio.

III.8.1 Direct Transfer Simulation

In Direct Transfer Mode, the robot picks the photovoltaic string from the conveyor and places it directly in the frame station. This scenario verifies the normal operating condition of the cell.

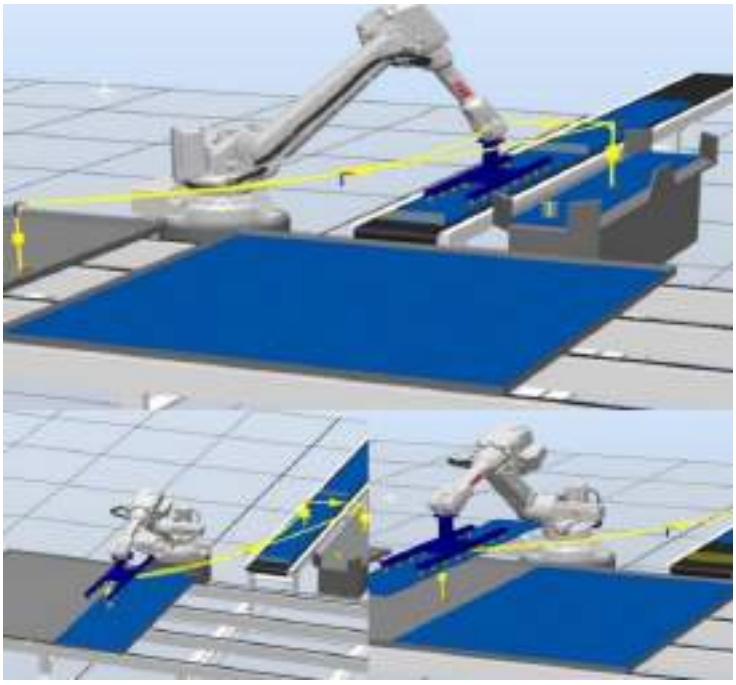


Figure III.6: Execution of Direct Transfer Mode.

III.8.2 Buffer Loading Simulation

In Buffer Loading Mode, the frame is considered unavailable. The robot therefore transfers the incoming string from the conveyor to the buffer area. This verifies the ability of the cell to avoid interruption when the placement station is not ready.

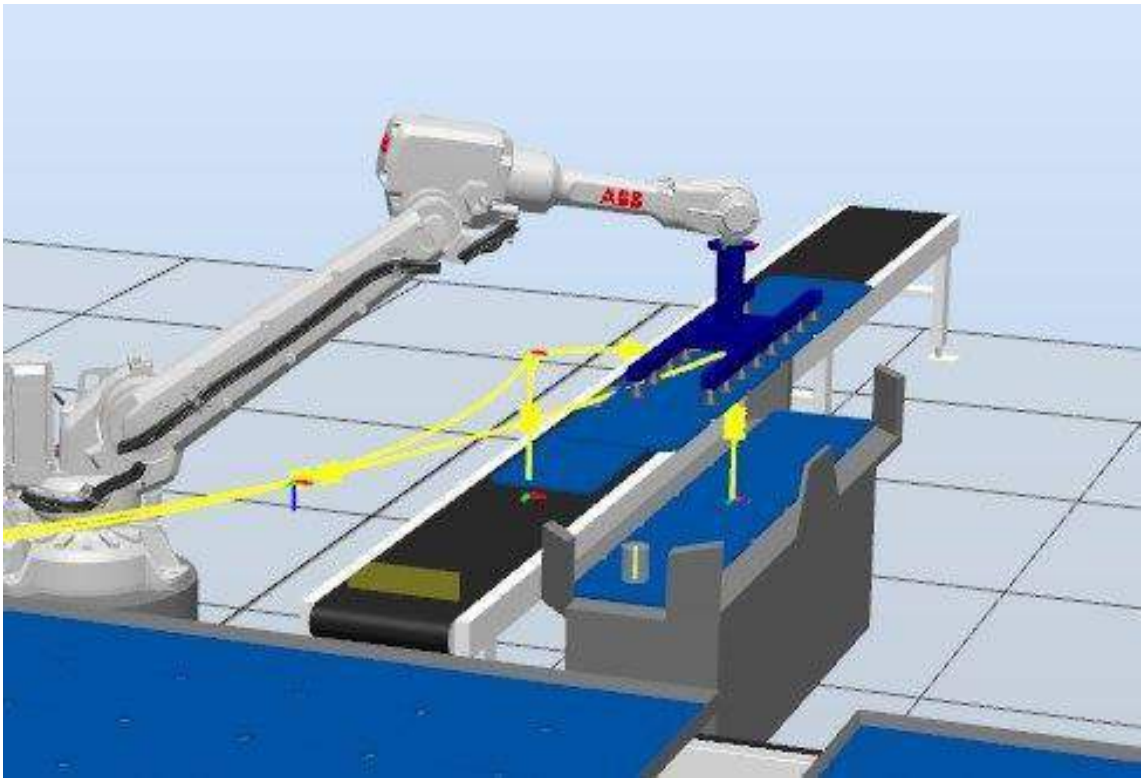


Figure III.7: Execution of Buffer Loading Mode.

III.8.3 Buffer Recovery Simulation

In Buffer Recovery Mode, the frame is available while the conveyor does not provide a new string. The robot retrieves a stored string from the buffer and places it in the frame station.

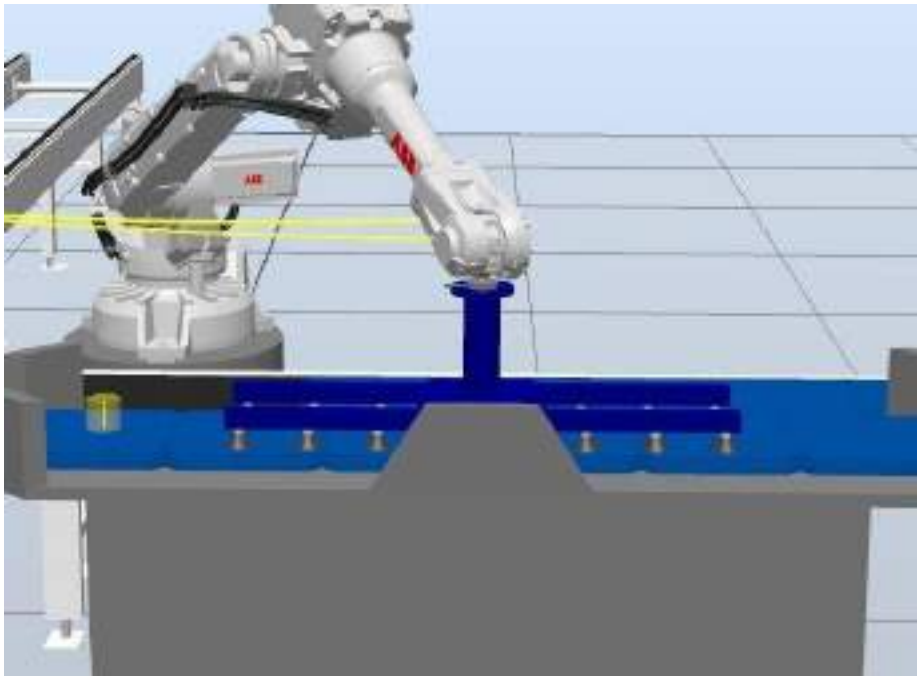


Figure III.8: Execution of Buffer Recovery Mode.

III.9 System Optimization

III.9.1 Speed Optimization

The selection of speed parameters was guided by the requirements of each stage of the pick-and-place process. Lower speeds were used near pickup and placement points because these operations require accurate and stable interaction with the photovoltaic string. Higher speeds were used during transfer movements to reduce cycle time.

The selected speed values are summarized in Table III.7.

Table III.7: Selected motion speeds.

Motion type	Speed
Pick and place operations	v1000
Intermediate movements	v3000
Transfer movements	v5000

III.9.2 Accuracy and Repeatability

Accuracy was improved through the use of predefined robtargets, fine zones at critical points, and dedicated approach and departure positions. These elements make the robot movement more stable and reduce the risk of positioning errors during pickup and placement.

Repeatability was checked by running the simulation several times under the different operating scenarios. The robot consistently reached the programmed targets and completed the required operations without visible deviation from the defined sequence.

III.10 Simulation Results and Performance Analysis

III.10.1 Simulation Results

The simulation confirmed the successful operation of the robotic cell under the three considered operating modes. The robot correctly executed the direct transfer sequence, the buffer loading sequence, and the buffer recovery sequence.

The interaction between the robot controller, station logic, and programmed paths remained stable during the simulation. No major trajectory problem was observed in the validated sequence, and the robot was able to return to the home position after each operation.

III.10.2 Performance Analysis

The implemented control strategy improved the flexibility of the cell because it allowed the robot to react to different production states. The use of station logic simplified the RAPID program and created a clearer separation between decision-making and motion execution.

The trajectory design provided smooth transitions between workstations. The use of buffer storage and recovery improved process continuity by reducing unnecessary waiting when the frame or conveyor condition changed.

III.10.3 System Limitations

Several limitations must be considered. First, the work was performed in a simulation environment, so it does not include all physical constraints that may appear during real implementation, such as vacuum losses, cable flexibility, mechanical vibration, calibration errors, and real sensor delays.

Second, the system uses predefined target positions and does not include machine vision or adaptive positioning. For this reason, the photovoltaic strings must arrive at known pickup positions. Third, conveyor tracking was not implemented, so the robot can pick strings only when they are stationary or virtually fixed at the pickup location.

Despite these limitations, the developed simulation provides a functional basis for future implementation. It also gives a clear framework for adding real sensors, PLC communication, vision-based detection, conveyor tracking, and physical validation.

III.11 Conclusion

This chapter presented the implementation and validation of the proposed ABB robotic pick-and-place cell in RobotStudio. The robotic program was organized around three operating modes: direct transfer, buffer loading, and buffer recovery. These modes allow the robot to respond to different production conditions and improve the continuity of the handling process.

The chapter also explained the sensor logic used to generate digital input commands, the RAPID program architecture, target point definition, motion strategy, and trajectory optimization. The simulation tests confirmed that the robot can execute the programmed sequences and select the suitable operation according to the workstation state.

The results show that the proposed system is a suitable basis for automated handling of photovoltaic strings. However, future work is still needed to validate the system experimentally and to improve it through real sensors, machine vision, conveyor tracking, and physical implementation on an ABB robotic cell.

General Conclusion

General Conclusion:

This thesis focused on the design and simulation of an adaptive pick-and-place system using an ABB robotic arm. The proposed application was related to the handling of photovoltaic strings and their placement inside solar panel frames. Since photovoltaic strings are fragile and require accurate positioning, the system had to ensure stable robot motion, suitable gripping, and safe operation inside the workstation.

The first chapter presented the general background of industrial automation and robotics. It explained the role of industrial robots in modern production systems, their main classifications, and their essential components. The chapter also introduced pick-and-place systems, their operating principle, main elements, advantages, limitations, and technical challenges. This theoretical part showed that robotic pick-and-place applications depend strongly on the correct selection of the robot, end-effector, sensors, and workstation layout.

The second chapter focused on ABB robotic systems and the tools used in this work. ABB Robotics was presented as a major industrial robot manufacturer, and the ABB IRB 2600 was introduced as a suitable robot for medium-payload handling applications. The chapter also explained the role of the robot controller, the RAPID programming language, and RobotStudio software. In addition, the adaptive control concept was discussed in relation to the proposed workstation. In this thesis, adaptation was mainly based on decision logic that allows the robot to react to frame availability, string presence, and buffer state.

The third chapter presented the practical design of the proposed robotic cell. The system was composed of an ABB IRB 2600 robot, a conveyor, a vacuum-based end-effector, a photovoltaic frame station, and a temporary buffer area. The robot was selected according to reach, payload, repeatability, and compatibility with RobotStudio. The vacuum gripper was selected because it is more suitable for handling flat and fragile photovoltaic strings with reduced mechanical stress.

The adaptive operating strategy represented an important part of the proposed system. When the frame is available, the robot places the photovoltaic string directly into the frame. When the frame is not available, the robot stores the string temporarily in the buffer area. Later, when the frame becomes available again, the robot can retrieve the stored string and continue the assembly operation. This logic helps reduce unnecessary waiting time and improves the continuity of the production flow.

RobotStudio simulation was used to validate the proposed design before real implementation. The simulation made it possible to check robot reachability, path feasibility, collision-free movement, and the general behavior of the robotic cell. RAPID programming was also used to describe the robot movements, vacuum gripper control, and adaptive sequence. Through this virtual validation, the proposed system was shown to be a suitable basis for an automated photovoltaic string handling application.

However, the work remains mainly based on simulation. Some aspects still require practical validation, especially the real behavior of the vacuum gripper, the exact cycle time, sensor response, and the mechanical stability of photovoltaic strings during movement. These points can only be fully verified through experimental tests on a physical robotic cell.

As future work, the proposed system can be improved by integrating real sensors, machine vision, and PLC communication. The adaptive logic can also be developed further by adding more advanced control algorithms, force feedback, or automatic correction of object position. A real implementation using an ABB robotic arm would allow more accurate evaluation of cycle time, gripping reliability, and production performance.

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