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Digital twin and its application on plywood production line

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ABSTRACT

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This master's thesis is about the role of the Digital Twin in product development. The product that is needed to develop in this project is plywood panel repairing line which is working is Raute Company. This machine is used in a step of producing plywood or LVL panels. Cartesian robots are working through the line to repair the defects on the panels. In order to boost the efficiency of the product line, high velocity and precision are needed. Therefore Festo toothed belt axes is replaced by linear motors.

In order to use the Digital Twin in improving the new design of the machine. Mevea software is utilized to create a real-time simulation. Mevea provides facility to connect the simulation to the controller that is designed in Simulink. The controller has played the crucial role in the simulation because the planning task and requirement of movements should be changed in controller design. Hence, it provides the access to update the system anytime.

The control system is designed based on controlling the position related to the velocity. It is important to control how to reach the target points. The electrical force that is generated by linear motors is controlled based on the velocity profile then send to the simulation to move the Cartesian motors. The results of the real-time simulation represent if the linear motor supplied enough force, the Cartesian robots move fast and reach the target points with acceptable accuracy.

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Sara Moghadaszadeh Bazaz

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TABLE OF CONTENTS

1 INTRODUCTION

In an industry when the new model of a machine is developed, it should be tested for different maneuver to analysis the performance, vibration, failure mode and effect analysis, maintenance, develop the control system, and parameter optimization. Making prototype to reach these goals is time consuming and it is not cost effective. In the last decades, simulation helps industry to analysis the development machines, products, or new design products. Many softwares are used to simulate. However to have efficient results it is necessary to have a virtual model that is close to the real model. Real-time simulation helps engineers to have a virtual model and tests near to the real system in the environment. The outcome of the real-time simulation shows the analysis of every known input. However in the next level of simulation, it is necessary to model the unpredicted physical product performance.

Digital Twin is the state of the art technology for analysis the past, understand the present and predict the future of the industrial products in their life cycle. Digital Twin collects data from manufacturing, maintenance, operations and environment to create a model of the system. The model that is created by Digital Twin is like the virtual prototype of the system that can continually adapt to change in the environment and operations. Then by applying the analytic, anomalies in the system are detected, then by determining an optimal set of actions it can predict the long-term planning for the model or system.

In each modeling the system, there are two aspects of the system those are connected to each other: physical system in real environment and virtual system in a virtual environment that has all about information of the physical system. (Grieves & Vickers, 2017) Some advantages of Digital Twin are Visibility that provides visibility into the operation of the machines and interconnection with other systems, it can be used to predict the future state of the machines, during the simulation, it is easy to answer new questions about various conditions that are impractical to create in real life, it is possible to document and communicate mechanism to understand and explain behaviors of an individual machine and achieve business outcomes in the context of supply chain operations including manufacturing, procurement, warehousing, transportation and logistics, and field service.

Before the actual manufacturing phase, it is possible to test and develop the machine by using Digital Twin. For this purpose, it should be used the data of the actual machine in the design phase. Therefore, it simulates a variety of operations and response of machine in whole life cycle of the machine. Digital Twin gives better knowledge about the information of different situations and it is the good way to find the suitable response to change conditions. In addition, it provides digital asset optimization and reduces the maintenance time and cost by preventing the overall maintenance. Therefore, the life of the machine is extended.

Figure 1.1 demonstrates the basic of the Digital Twin and its role in developing the product. The outcome of the Digital Twin is used to specify the reason of the failure or performance problems, define optimized maintenance schedules, evaluate results of different conditions in the system, demonstrate and provide data that is impossible to measure with sensors. After this, by using the outcome from the operator and machine the Digital Twin is updated with suitable data. Therefore, it communicates the data from the scaled Digital Twin to the company easier and better.

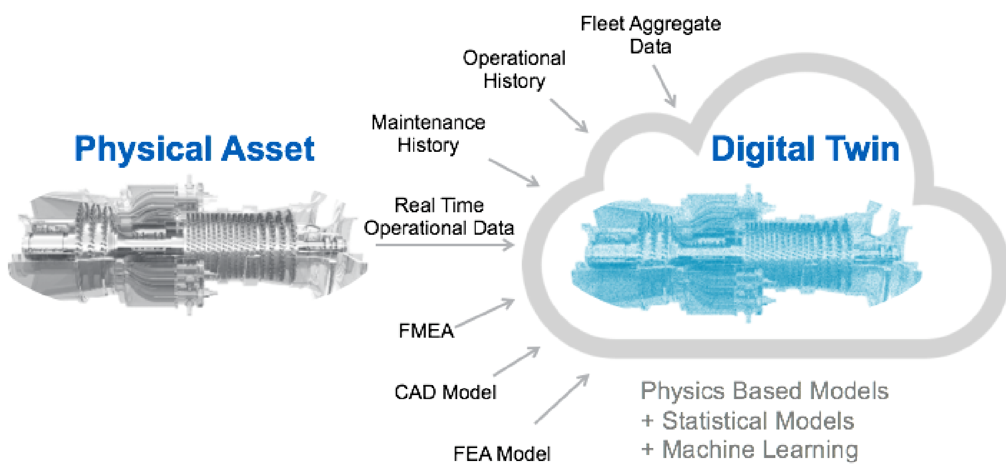

Figure 1.1. Relation between real and virtual model in Digital Twin

Raute is a company which is working on the wood products such as veneer, plywood, laminated veneer lumber (LVL). Raute’s position in the industry is in high level and also Raute is a global market leader in the plywood industry. Raute is equipped with modern technology to develop and improve the production and maintenance line. Technology services play a considerable role in market and development of technology so follow the modern technology in production and repairing lines causes high quality and quantity in the final product in order to reach the customer satisfaction. " In future, Raute will also focus on modernizing competitors' equipment with Raute's technology." (Raute, 2017)

Panel repairing line is one stage in producing plywoods. Panel repairing machine is used to find defects on plywood panels and repair them full automatically. The machine is equipped with four Cartesian robots to repair the defect on plywood panels by drilling/machining and filling/puttying operations. The Cartesian robot in current machine works with Festo toothed belt axes to travel on the line in specific limited paths to reach the target point. Figure 1.2 depicts the panel repairing line which is equipped with Cartesian robots and Festo toothed belt axes.

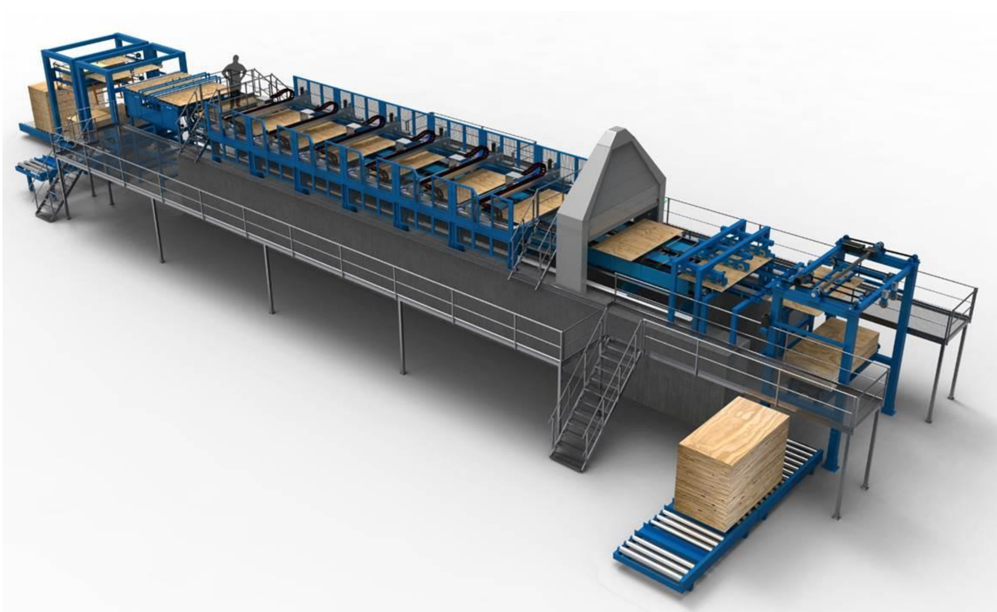

Figure 1.2. Panel repairing line in Raute

In this project the Festo toothed belt axes is replaced with linear motor in order to move faster and reach the defect place and doing the repairing operation more accurate than the current machine. The objective of this project is to create the virtual prototype of the panel repairing line with Cartesian robots and linear motors then find the maximum velocity that Cartesian robot can run on the convey to the defect without losing position accuracy.

1.1 Research questions

The main aim of this research is to create a virtual prototype of the panel repairing line that is move by linear motor in order to answer the main question that:

By using linear motors to move the Cartesian robots, are they run faster and reach the target points more accurate than the previous model?

In addition, the other sub questions will be answered in this survey.

1. How much is the maximum running velocity of the Cartesian robot with the same linear motor?
2. How much is the position error of the Cartesian robot in different velocities?
3. How much is the position error of the Cartesian robot in different forces?

1.2 Research methods

In this thesis, a set of softwares is used to build the virtual model of the real product. In the design section, CERO is used to create the graphics of the parts of the model, then the multibody system is arranged in Mevea Modeler to analysis the real-time simulation in Mevea Solver then Simulink is connected to Mevea Solver to real-time control the Cartesian robots. Figure 1.3 shows the procedure of making the virtual prototype and the role of Digital Twin in this analysis. As it shows, the Digital Twin is used to update and modify the virtual model after analyzing the real-time simulation the test the model again and repeat this procedure until to get the suitable results.

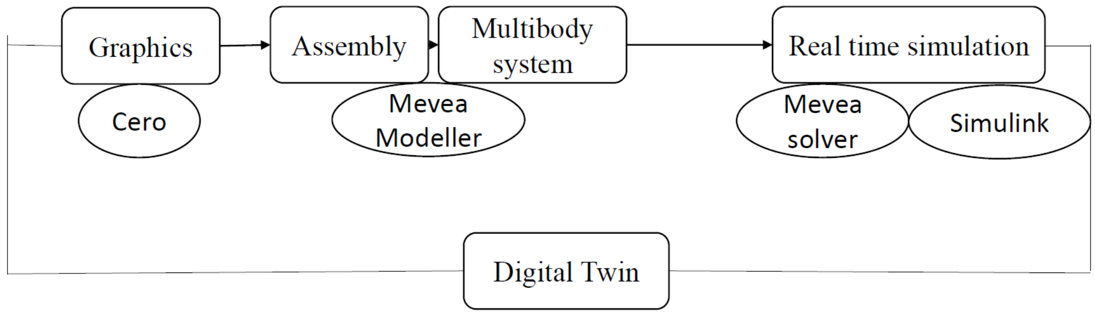

Figure 1.3. The procedure of creating the virtual prototype

2 METHODS

Producing is the complicated and expensive process in the industry. In the recent years, companies effort to develop the methods of the producing from the design phase to maintenance and marketing. Customized product development is one of stages in developing products in order to fulfill the customer's requirement. The Digital Twin provides the facility for interaction between companies and customers in all lifecycle phases of generating the product. In following the role of Digital Twin in product lifecycle management is described.

2.1 Use of Digital Twin in all life cycle phases

Product lifecycle management or PLM is the process of managing the product in all life cycle stages such as design, production and maintenance. (product-lifecycle-management, 2017) In 2003, Dr. Michael Grieves introduced the concept of the Digital Twin as a virtual model that represents the actual model by using data and information, which are collected from the actual model for analysis and predict required in the maintenance and development of the virtual product to design and manufacture the physical product. The Digital Twin is used in variety engineering fields to design a new product or develop it to operate in conditions and analysis the behavior of the system in different conditions are not timed and cost effective to experiment with physical prototypes. (Grieves, 2014, p. 2)

2.1.1 Design phase

During the concept design of a product some data and models are created which have formed the basis of the Digital Twin. This information is collected from requirements and experience from previous models, then used for a first abstract design of a functional view of the product. After developing the design of the product it could be validated by virtual prototype. (Hehenberger, et al., 2016, p. 70)

Using the Digital Twin in geometry assurance is one good example in this phase. Geometry assurance is the process to minimize the influence of geometrical variation of the product. The geometry assurance process for every product consists three phases: design, pre-production and production these are shown in figure 2.1.

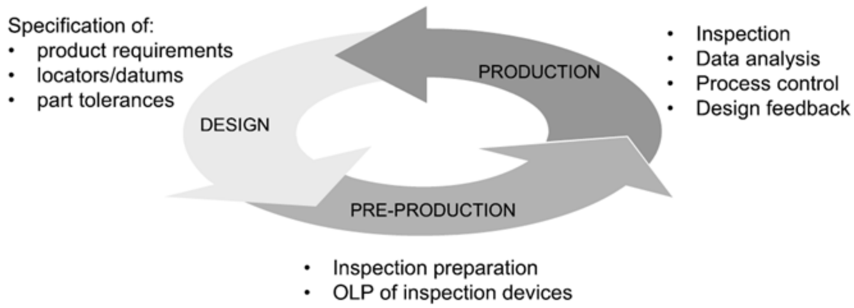

Figure 2.1. The geometry assurance process (Söderberg, et al., 2017, p. 137)

In the design phase the whole concepts of the product are analyzed and the product requirements for manufacturing are defined. It also contains the information of the assembly and tolerances and position of location of each part. In pre-production and production phases, the physical model is improved. Because changes in the production phase are more expensive than the design phase, therefore using a digital geometry assurance process decreases the costs.

The Digital Twin consists all information about the physical and functional description of a system which can be used in whole lifecycle phases of the product. One aim of the Digital Twin is a simulation and transfer of data from one life cycle phase to the subsequent phase. This digital development provides the situation to connect the sensors, machines, workpieces, and IT systems in a product. This connected system is called as cyber-physical systems can work with standard Internet-based protocols, then analyzed data to predict failure, reconfigure and adapt to changes. It also boosts availability of data that provides better maintenance. By using Digital Twin in the design phase, it is possible to represent geometry, analyze variation and sensitivity in kinematic relations and finite element analyses. It is possible to use the data of parts from the previous projects in Digital Twin.

Locating scheme optimization is one aspect of design phase that is related to the physical contacts between fixtures and parts in an assembly. Locations schemes are defined as a transfer function between input and output variables and controls the robustness of a mechanical assembly. Another step of the design phase is variation simulation that shows how part variation distributes in the assembly that is calculated by using transformation matrices. Usage of Digital Twin in pre-production is to inspect preparation and off-line programming (OLP) of coordinate measuring machines (CMMs) and scanners. Inspection features and programs are generated from the Digital Twin geometries. Information from variation simulation shows where to measure and how to measure is defined by automatic collision free path planning. The virtual assembly model and inspection data are combined together to control production and detect the errors then correct them in product phase. During production, the Digital Twin is fed with inspection data from the final product. This is used to analyze if product defects emanate from assembly fixtures and decide what fixture and what locators that have caused the defect. (Söderberg, et al., 2017, pp. 138-140)

2.1.2 Engineering phase

In this phase, executable simulation models are created. These models should contain enough details to answer engineering questions about the product. Depends on the specific question sometimes different models are created to solve the problem. In complex systems, domain specific models have to be used together with extended system models. In the case of the product, many simulation models are created to analyze the specific purpose. Simulation models such as: mechanical model, Electrical model, Hydraulic model, system models to simulate whole power transmission.

In complex systems, it is necessary to be disciplines between the models. To provide a consistent source and use it for all inputs in all models, they should be stored in a unique place. The source consists the information about the initial design parameters and information of all models those are created in developing process. Nevertheless, in real system it is not possible. The Digital Twin as a common storage for all digital artifacts is using in the developing process of the mechatronic systems. (Hehenberger, et al., 2016, p. 71)

In following four examples of using Digital Twin in engineering phase in aerospace, mechanic and mechatronic fields are described. First example is about using the Digital Twin to predict the structural performance of the future model of 25-0001D/I airplane in series of missions. The Digital Twin consists of different components like heat transfer model, dynamic model, fatigue model and stress analysis model that are connected to each other. In simulation the possible interactions like CFD and FEM models are considered. The Digital Twin has two sets of information to predict the evolution of material states and progression of damage during the virtual flight. Because of the model has some uncertainties during the actual flight so the Digital Twin will interpret uncertainties in inputs into probabilities of obtaining various structural results.

Digital Twin can use for any length of flight time in order to predict the maintenance needs and repair costs for the aircraft. To reach the aim of the project it is important to have the modeling of the response of the structure to all of the applied loads for Digital Twin. (Tuegel, et al., 2011, pp. 10-12)

In another example the Digital Twin spark ignition (DTSi) in used in high speed vehicles simulation to gain the better performance with high fuel efficiency. Spark ignition is the vital system in an engine because the time between two sparks and the number of spark per minute effects on the engine performance. In the DTSi, spark timing is controlled by computer to obtain optimum combustion. This system improves thermodynamic efficiency, reduce exhaust emission, reduce probability of failure in ignition system, and reduce specific fuel consumption. Results show by using this system the maintenance cost is reduced because parts move less so there is less friction and wear. Moreover, it minimized emission levels so pollution is reduced. (Zambre, et al., 2014) (Prabhkar, et al., 2014)

The third example is about using the Digital Twin in Additive Manufacturing in order to simulate and validate microstructure and mechanical factors those affect properties of additive manufactured products. By using the Digital Twin to simulate the effects of the changing factors in AM products, time and cost and error or defect in final product are reduced. The information is needed to build the Digital Twin. Data is gained from simulation of heat and material flow, simulation of solidification, grain structure and texture evolution, modeling of microstructure and properties, and calculations of residual stresses and distortion. (DebRoy, et al., 2017)

In robotic a system that is used to insert a peg in the hole, it is needed to detect the hole then insert the suitable pig. In order to reach this goal, Virtual Testbed is used to develop control algorithm in order to prevent the consequences of this problem like failure or damage in the parts. A Digital Twin is used to create a virtual set up by virtual modeling a physical manipulation in the virtual application environment. This virtual set up is used to test and optimize the algorithm in simulation. Then the algorithm for peg in hole is developed to have a fitted peg and hole. Digital Twin is used to validate this algorithm. Then the algorithm is transferred to the real robots. The experimental results depict that the simulated setup can predict the behavior of the physical setup. (Grinshpun, et al., 2016)

In the last phase of product engineering, when the all components should be integrated so they should fit seamlessly together. If all physical components could not be ready in the same time to test the product, we can use Digital Twin as the virtual component instead of the physical component in the system. Another application of the Digital Twin is in assembly phase. It is easy to detect mounting problems in advance by digital artifact of physical components. So before presenting the physical model it is possible the model integrated into the model representation from the Digital Twin to check for inconsistencies. Before using the product in a real environment, it is possible to simulate the operating environment and test the system.

2.1.3 Operation phase

The main advantage of the Digital Twin in mechatronic systems is that the information created in design and engineering phases can be used to evaluate during the operation phase. In addition, it can be used in improving the product. For instant if, the application of the product is changed so the product should be improved. In this case it is possible to modify the existing models. It is also possible to collect the data during operation part as part of the Digital Twin then used it to update the model for real operation conditions. The Digital Twin provides the situation that use the real data as verification input to improve simulation model.

Another application of the Digital Twin is online monitoring during operation. It is common to use sensors for monitoring to report a malfunction but sometime sensor data in not sufficient or it is not possible to use sensors. So it is possible to use virtual sensor data to achieve the real-time data from operation condition. The Digital Twin is also used to identify failure modes in mechatronic systems therefore time and cost for maintenance is reduced. (Hehenberger, et al., 2016, pp. 72-73)

2.1.4 Service Phase

Because the Digital Twin provides a smart view models of the systems, so it can be helpful for users in different fields. The information about monitoring or predict the malfunction is used to enhanced service process to prepare adequate spare parts. (Hehenberger, et al., 2016, p. 73)

2.2 Using Digital Twin in marketing

There are many benefits in using the Digital Twin in producing process by companies. It provides complete digital footprint of products from the first stage of design and development through the whole product life cycle. Therefore companies enable to determine physical issues and predict more accurate results so create the better quality product with less cost. The role of the Digital Twin in areas of business is expressed in following:

In quality area, Digital Twin improves overall quality of products and able to detect and predict when or where faults happen in quality. Digital Twin reduces the cost of operation by doing faster design cycle, improve performance of manufacturing process. Although the quality of the product designed is improved. The Digital Twin manage better warranty cost by better overview about the equipment for servicing then more accurate in warranty determine so the warranty cost is decreased also costumer is got better services. In the new production area because the time and cost of the produce process is reduced so the time to introduce the product in market is diminished. In addition Digital Twin effects on supply chain by better recognize long-lead-time components. All in all the revenue is increased because customers can connect straight to the company to order and surveillance every detail in the product. Furthermore, because of using Digital Twin in all life cycle steps so the speed of the development and transfer new designed product to the market is increased. Moreover marketing margin is increased due to ability to make rapid low cost prototype so the cost of R&D is reduced and by analyzing the material, it is possible to determine lower cost raw material or provide facility for customers to choose suitable demand materials.

The Digital Twin in produce processing boosts monitoring and visibility facilities so the cost of quality is decreased. For instants, the real-time data from sensors detects faults or errors then by sending to Digital Twin the produce processing is improved. Digital Twin provides greater asset efficiency in marketing. Predict optimal maintenance can increase performance and reliability of manufacturing devices. Ability to monitoring helps to optimize workforce assignments and schedule. Accurate real-time analysis prevents error in maintenance then reduces the cost of maintenance. (digital-supply-networks, 2018)

2.3 Structure of the Digital Twin

As Dr. Grieves has mentioned in his white paper, “Digital Twin is understanding relationship between a physical product and its underlying information to a critical component of an enterprise-wide closed-loop product life cycle.” (Grieves, 2014, p. 1)

In order to use the Digital Twin in simulation a behavior of a system or machine, first, the simulation model is arranged to link collection of artifacts in order to figure the specific problem out. The artifacts could be engineering data, behavior description or operation data. The Digital Twin evolves with the real system in whole life cycle of mechatronic system and provides the current knowledge about it. Therefore, the Digital Twin expands the model-based systems engineering to find the solution in operation and service phases of product life cycle. (Grieves, 2014, p. 3)

A full Digital Twin model consists elements such as real space, virtual space, the connection for data flow from real space to virtual space, the connection for information flow from virtual space to real space and virtual sub-spaces. Figure 2.2 depicts the ideal concept of the Digital Twin. (Grieves & Vickers, 2017, p. 92) Therefore, the first step and requirement is the physical machine (product) in real space then in the second step, virtual machine (product) is created in virtual space. CAE software is used to create the lightweight model by selecting the geometry, adding behavioral characteristics in order to visualize and simulate the performance capability. Modeling this lightweight model consume less cost and time because it does not contain unnecessary details. In the third step it should be bilateral connection of data and information between the physical machine (product) and virtual machine (simulated model). For instant, when the machine performs operations in real space, data is collected to understand the properties of the operation like how much speed and what kind of force is applied. (Grieves, 2014, pp. 4,5)

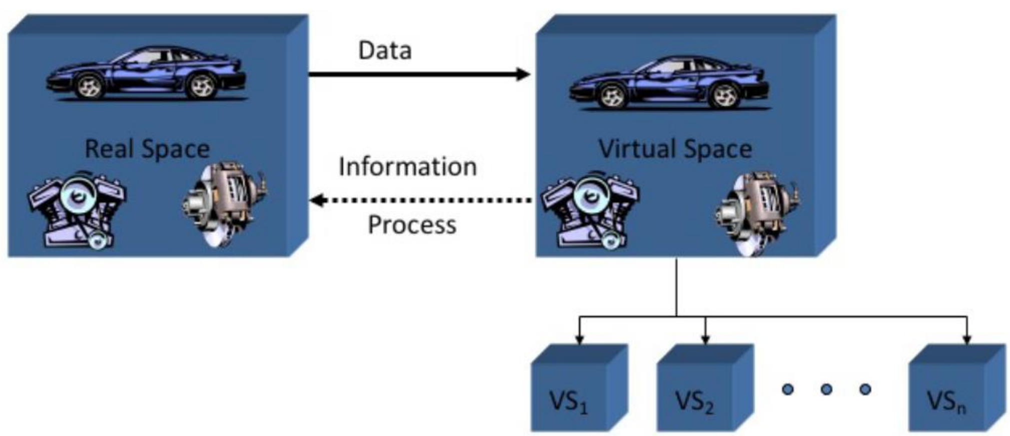

Figure 2.2. Ideal concept of the Digital Twin (Grieves & Vickers, 2017, p. 93)

Figure 2.3 depicts three types of the Digital Twin. Digital Twin Prototype (DTP) and Digital Twin instance (DTI) are two main types of the Digital Twin. In the Digital Twin Prototype, all information of physical product is used to create the virtual product. This information could contain all properties of product such as 3D model of the physical product, or information about maintenance and service, or bill of disposal. The properties are shown as a different layer of the model in figure 2.3. However, in the Digital Twin instance, only a specific physical property of the product is used to create the Digital Twin to predict the future behavior of the system. For instance, all dimensions and tolerances of the whole physical system form the 3D model as it is shown one property in figure 2.3. The bill of material shows the all properties of materials of the current and past components and operational data that is captured by actual sensors.

All of the DTIs are aggregated in Digital Twin Aggregate (DTA). Digital Twin Environment (DTE) is application space for operating on Digital Twins in different purposes like predictive the future behavior of the product and interrogative to apply on DTI as the realization of the DTA. (Grieves & Vickers, 2017) In continue four aspects of Digital Twin are discussed.

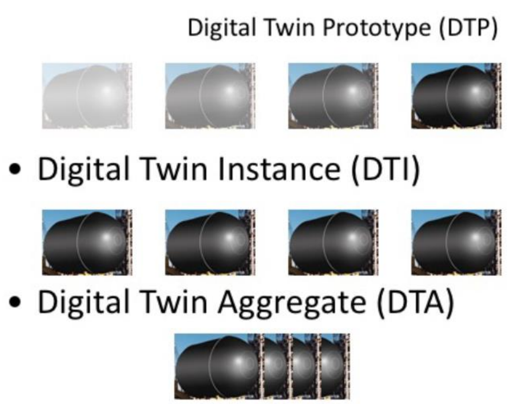

Figure 2.3. Digital Twin types (Grieves, Vickers, 2017)

2.3.1 Principle approach and benefit

Digital Twin is the smart technology to boost productivity of operations. The Digital Twin is used in processing phase-specific simulation task as the input data. Figure 2.4 shows the principle approach of the Digital Twin and contains digital information so it has ability to close the loop from operation and service back to design of new products. The Digital Twin is the basis for simulation-driven assist systems in operation phase. (Hehenberger, et al., 2016, pp. 63-66)

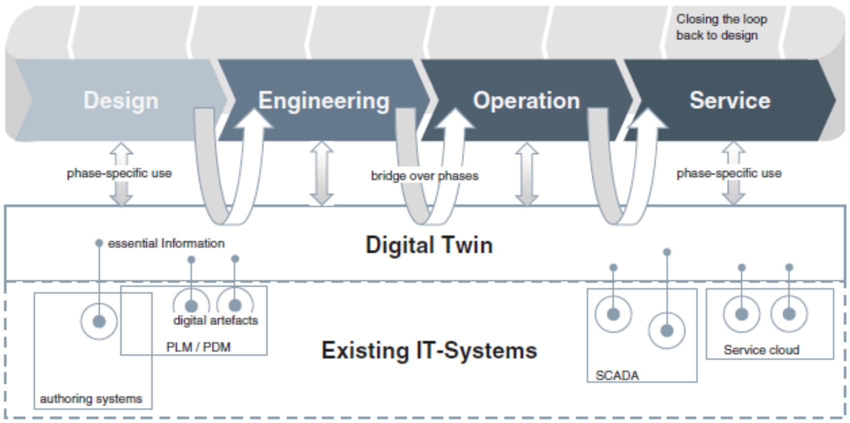

Figure 2.4. The Digital Twin uses the essential information originating from different IT systems and makes it available for succeeding phases (Hehenberger, et al., 2016, p. 67)

2.3.2 Architecture of the Digital Twin

The Digital Twin is used to answer the different specific question in all life cycle phases of product. For example it is used to validate the functionality of different components of the product. ‘’ The Digital Twin is a product feature, which is planned from the early stages.’’ The important step in building the architecture of the Digital Twin is to collect the suitable data and simulation models for a real application. Also some new application could be realize by Digital Twin because of this architecture. (Hehenberger, et al., 2016, pp. 67,68)

2.3.3 The principle methodology of the Digital Twin is based on following aspects

The principle methodology of the Digital Twin is based on following aspects. In first step the information is interchanged by models. This step is called model based development. This models are modular so it is possible to use them in different situations in order to reach this purpose a model management system needs to keep them up to date and allows to find the suitable model for the application. (Hehenberger, et al., 2016, p. 68)
The Digital Twin simulation architect is defined by the structure of simulation models and links all of them so this structure connects the digital artefacts to the functional real application. This structure is extended with the real models and associated data by Model-

Based System Engineering (MBSE) techniques. Finally the Digital Twin would be part of the physical product. Therefore it can solve the future problems in later phases. For instance, it is used as an assistance system for operators or in maintenance phase. So it shows some contents of the Digital Twin could become part of the system. It is the way that the Digital Twin links the digital world with the physical system.

As it mentioned the Digital Twin is like a modular which means it transfers data and information into other Digital Twins. In other words the data is gained in one phase can be used in another phase or application. The same data can be used in various models in parallel. The modulator chooses the right data for each purpose. (Hehenberger, et al., 2016, p. 69)

2.4 Simulation aspects of the Digital Twin in Mechatronic systems

Nowadays, software and network connectivity develop the functionality of mechatronic systems. In development process after designing, simulation the model is helpful to validate system properties. In this case, simulation is used to optimize operations and predict failure in all life cycle.

In every mechatronic systems in first phases of design, it is necessary to use multi-domain and multi-level simulation in order to validate properties in all life cycle phases by virtual tests therefore the Digital Twin is used in the two dimensions of time and level of details aspects. Digital Twin focuses on below factors:

- By using this simulation over different levels of details with all involved discipline in all life cycle phases, the time-to-market is reduced.
- The Digital Twin should be designed in its principal structure and in its own architecture. It uses the pure data from design phases and the data is collected during operation and service by simulation models. These data contains system behavior, performance evaluations and quality considerations. The task of Digital Twin is to provide a connection between different models and data in different granularities then keep them stable.

- The architecture of Digital Twin contains different models with different granularity and connects them.
- The Digital Twin is like a bridge between development and operation in order to optimize mechatronic products in less time and cost. (Hehenberger, et al., 2016, pp. 59-63)

2.5 Multibody dynamic systems and Digital Twin

To analysis multibody dynamics, engineers create virtual models that can reproduce actual phenomena and used the simulation results using these models. These models are called virtual prototype in the CAE field. However, sometime these models are not directly connected to the actual industry environments. The measured data is gained offline from the actual product. So based on these data, the virtual model is created or simulated then the results from the simulation are documented and used for developing or maintaining the real product. However the process in the Digital Twin is connected that means data measured and received from several different sensors on the actual product then they are transmitted to the Digital Twin. It is also possible to analysis the situation of the unmeasured parts by using the Digital Twin-based simulation. These results are used to maintenance, development, determine which parts need to replace, and expect lifetime of a product. The updated data is gained from the Digital Twin is applied to the actual product or they are used to create different products in different applications.

In the Digital Twin concept, the actual and virtual model is not separated, so Digital Twin is like a mirror between them. The Digital Twin should be able to detect the changes of actual product, analyze the actual product situation, or provide immediate results that can improve the state of the actual product. In some cases, the actual product consists different systems such as electrical systems, mechanical systems, and hydraulic systems, so the Digital Twin should analysis whole system-level and analysis in multi-disciplinary with fast speed. (future-digital-twin-cae, 2017)

One example of using Digital Twin in multibody dynamics modeling is in unpredicted contact force in intelligent robot. The simulated robots can embed external forces applied by the environment on their manipulators. Researchers unified methods of multibody dynamics modeling, advanced modeling and virtual reality to simulate the compliant robotic manipulations. When the position-controlled robot is working, it is in evident some interaction forces occur in the contacted environment. There is a limitation in simulator in stiff motion tracking. Simulated robots are not able to capture and reflect important dynamic effects that are used to determine the reactive behavior of physical force-controlled robots in interaction with external forces. So by integrating the 3D-simulation and compliant robotic manipulations it is possible to decrease some limitations in position controlled robots. So by integrating the 3D-simulation and compliant robotic manipulations it is possible to decrease some limitations in position controlled robots because of properties of 3D-simulation like repeatability and intrinsic safety. Uncertainty in position and geometry reduced the workspace of the robot but manipulator can maintain a physical contact with the environment while exerting a force that is suitable for a safe and successful task completion. Virtual testbeds provides interaction capabilities to exchange mechanical energy between manipulator and its environment. This facility can be developed based on different simulated applications through rapid prototyping therefor avoids complexity and reduces time and cost. So it is possible to use the compliant behavior of a simulated robot to improve the interaction capability of the physical position-controlled robot in actual applications. For reaching this aim, sensed interaction forces acting on the physical robot drive its compliant Digital Twin in real-time. A programmed joints motion is used as input for Digital Twin to follow the reactive compliant joints trajectories. So physical robot embedded external forces without any changes in its control structure. So this virtual testbed with Digital Twin is an expandable supplementing loop which provides facility to intuitive and immersive observes for the information that describes the compliant robot behavior.

This paper has started from 3D simulation of compliant robots to simulate an interactive behavior of multi-body systems between robot and its operational environment. The first phase in this stage is modeling the virtual environment. Multi-body modeling based on constraint forces is used to introduce relative velocity between pairs of bodies. This method is suitable in complex systems to investigate physical interactions between bodies. Constraint forces are applied on bodies which need to prevent the penetration between them. In this phase, a robot model is an unactuated so it should be controlled undesired behaviors. A Jacobian matrix maps vector of joints velocity into the vector of Cartesian velocities of the mass center of the one segment of the manipulator links. The controller of each joint of a Digital Twin which contains the information about the twin links articulated is used to form the Jacobian matrix.

This diagram in figure 2.5 depicts the modeling of the dynamics of torque-controlled robots. The block of the physics-based multi-body dynamics simulation consists the Digital Twin dynamics and environment dynamics which are in contact with each other. τ_d is the desired joints torques and τ_a is the available joints torques. As it is shown in this diagram, the aim of this simulation is to control the robot to reach the desired torque in joints. The scenario of the task for the robot is fed to the control system as an input then by using motion control to control the torque then send the output of the controller to the multibody dynamic simulation to get the outcome of the simulation then send the robot states to the motion control as a feedback of the system then this process is repeated and updated in all cycles until reach the desired task. (Kaigom & Roßmann, 2016, pp. 1000-1005)

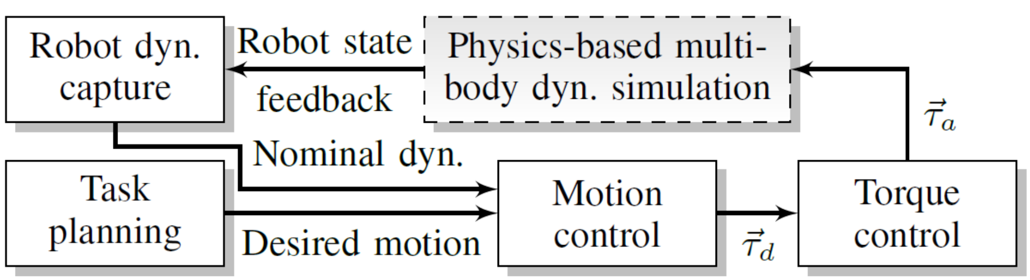

Figure 2.5. Coupled modeling paradigms for a holistic simulation of compliant robots (Kaigom & Roßmann, 2016, p. 1002)

In addition, figure 2.6 and 2.7 illustrate the simulation of torque-based control with using the Digital Twin as a link between simulation model and physical model.

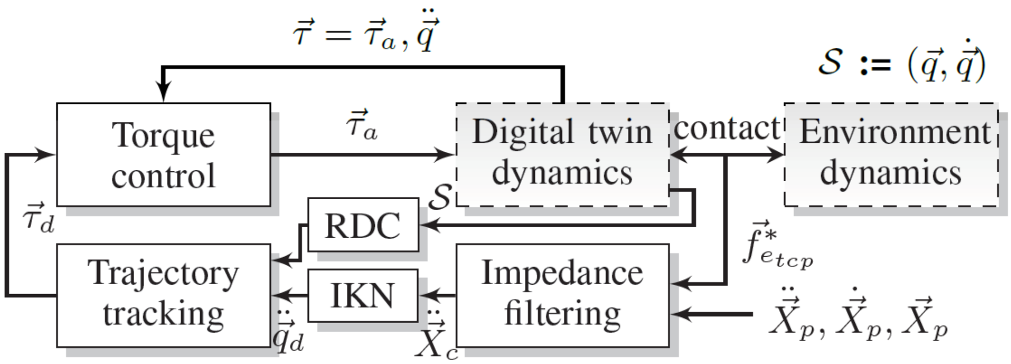

Figure 2.6. Torque-based impedance control (Kaigom & Roßmann, 2016, p. 1003)

In figure 2.6 the sub-index p shows the planned motion information (position, velocity and acceleration) as the inputs of the system. $\ddot{X}_c$ is the commanded TCP (Tool center point of the manipulator) acceleration and $\ddot{q}_d$ is desired compliant joints accelerations. IKN refers to inverse kinematics at acceleration level with null-space stabilization based on the right pseudo-inverse of *J*. Desired joints torques τ_d is obtained from torque-based trajectory tracking approaches so it should follow the desired compliant joints trajectory. Available joints torques are the input of the Digital Twin in multibody dynamics simulation.

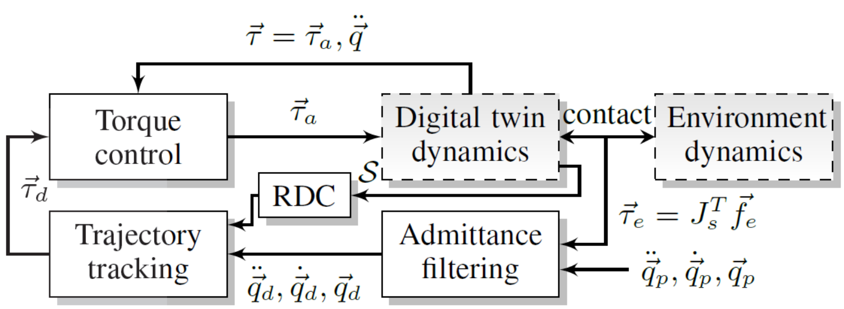

Figure 2.7 Simulation of torque-based joints admittance control (Kaigom & Roßmann, 2016, p. 1003)

In figure 2.7 τ_e expresses an external joints torques that is obtained from the action of the vector of the equivalent external forces ($\vec{f}_e$) on the center of the twin links which is mapped with Jacobian matrixJ_s^T. $\vec{q}_p$, $\dot{\vec{q}}_p$, $\ddot{\vec{q}}_p$ define planned joints trajectories and they are using as an input for the admittance filtering. In addition the output of the admittance filtering are desire compliant joints trajectories $\vec{q}_d$, $\dot{\vec{q}}_d$, $\ddot{\vec{q}}_d$ and they are used as an input for trajectory tracking to obtain desired torque that should follow the commanded compliant joints trajectories in order to obtain the desired joints admittance.

In simulation process, the physical robot and virtual robot (its twin) are doing same activity of its application (move down to insert a pig in the hole). Physical robot estimates the real equivalent contact force that is obtained from interactions between hole and peg. This equivalent contact force (f_{e_p} is sent to the twin as UDP (User Datagram Protocol) packages in real-time, UDP is the simple transmission model without junction and with a minimum of protocol mechanism, so it is used in time-sensitive program because close the packets is more accurate than waiting for delayed packets,; (techopedia, 2017) each time step (time step is 2*ms*) then it is mapped from the twin TCP to the center of mass frame of the *p*-th twin link. f_e and Jacobian matrix (J_s^T) are used to obtain the real external joints torque which are applied on the dynamics of the Digital Twin. In this method the real force is exerted as external force into the simulation so the comparison between joints control torques in the real robot with its twin is easier. Results of the simulation indicate both real and simulated joints torques always agree during the insertion task.

Figure 2.8 depicts the diagram of the relation between simulation through Digital Twin and real model. Results in the paper show physics-based virtual testbeds can predict the interactive behavior of force-controlled actual robots by using dynamic equations of the robots. (Kaigom & Roßmann, 2016, p. 1005)

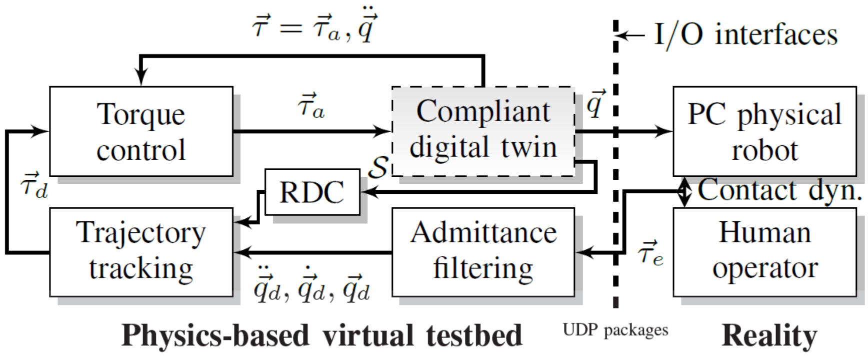

Figure 2.8. Manual guidance of a position-controlled robot by using its compliant Digital Twin (Kaigom & Roßmann, 2016, p. 1005)

2.6 Real-time simulation and Digital Twin

Experiment able Digital Twin is the state of the art technology is simulation-based development and operation of complex technical systems in order to design, programming, control and optimize the interaction with working environment. Experiment able Digital Twin consists of virtual testbeds and Digital Twin.

Simulation of entire life cycle of complex systems includes simulating the various stages of life cycle of the product in different environments by various simulation domains and engineering methods. Figure 2.9 methods that are used like sim-based engineering, sim-based optimization, sim-based control, virtual test bed and system design. The scope that contains all components, complete system and environment. then the application of the product, after that six stages of the life cycle such as design, development, production, marketing, training and operation. The next step is the field that product is using there, then users who are working as service maintenance, operator, technician and development engineer. The last step is the infrastructure in server, machine, mobile and the virtual reality. Therefore, if only one specific application is the issue in simulating, simulation is enough but when more than one aspects of the simulation is necessary in the same time or it needs to combine different simulation domain, the simulation is not enough so using Digital Twin in the center of the development process is the solution of this problem.

For instants, to simulate a The first step of the life cycle of a Digital Twin is the system design that can be a simple animation then using the simulation for overall performance analysis and finally to analysis details, combine rigid body and FEM simulation. Using this technology is cost effective, and caused design the better and reliable intelligent system that can supervise itself. ''A Digital Twin contains models of its "data" like geometry, structure, its functionality like data processing, Behavior and its communication interfaces.'' (Schluse & Rossmann, 2016, p. 1)

Figure 2.9. Different dimensions when using simulation technology throughout the entire life-cycle of a system (Schluse & Rossmann, 2016, p. 1)

Figure 2.10 shows the new architecture for simulation to reach close to reality Digital Twin that contains block oriented simulations, discrete event simulations, or FEM analysis methods. Moreover, the same Digital Twin is used to design and fulfillment the data processing algorithms. These algorithms are the natural part of the virtual twin. The resource data of the Digital Twin could save and update the simulation models to implements the algorithms. (Schluse & Rossmann, 2016, p. 4)

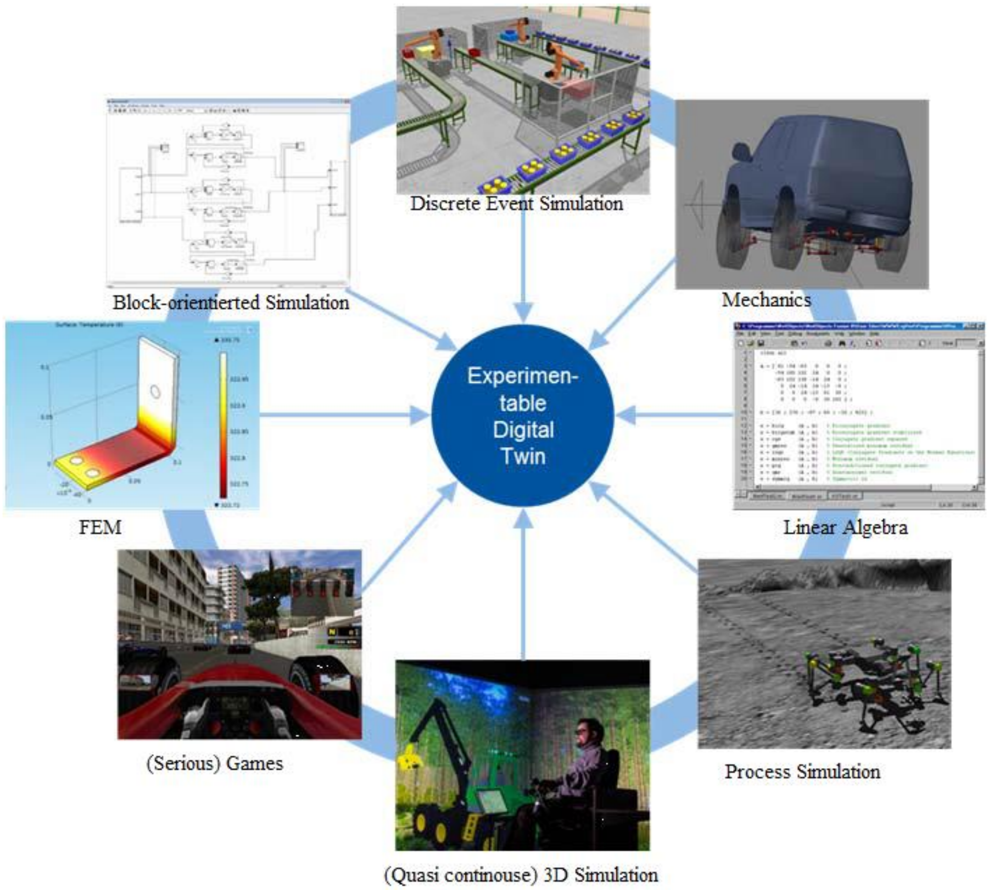

Figure 2.10. Different simulation algorithms and systems are used to realize close-to-reality digital Twins at different levels of detail (Schluse & Rossmann, 2016, p. 4)

In following the simulation aspects of the Digital Twin in Mechatronic systems are explained.

2.7 IOT and Digital Twin

Nowadays, The Internet of things is playing important role in whole product lifecycle that consists development, test and analysis, manufacture, operation and maintenance. Connecting to the cloud provides facility for connected devices to gain incomparable functionality. In addition, this technology opens the new door to the business and market in many companies. The application of the IoT is limit and it is using mostly in simple applications. Meanwhile the corporation of simulation and IoT creates Digital Twin that is able to improve the product in wide variety fields. The role of simulation is to create the virtual prototype of the complex system with all details. In addition the model of the surrounding environment is created.

Using simulation in designing and developing products is the crucial step in produce products in industry. The simulation provides the low cost way to analyze and evaluate several different alternative designs before making the physical prototypes. A technology to connect the many systems is IoT that is used to connect the machine (product), sensors, and actuators through the Internet. So sensors capture the data through the Internet by IoT technology then these data transmit to the simulation to analyze the operation and optimize the performance and maintenance in real-time.

The simulation-based Digital Twin contains physical product, simulation models and the connections that provide transmission between them. Therefor the Digital Twin is the developed simulation model that is built to duplicate the current condition of the product. The collected data and information by sensors are used as real-time boundary conditions for the Digital Twin. Then the outcome of the Digital Twin is calibrated to use in real space operations. The Digital Twin able to predict the performance problems, maintenance schedules, failure modes. In addition the Digital Twin is used to evaluate results of operation performance and provide information that is not possible to collect by sensors.

ANSYS illustrates how to use a simulation model as a Digital Twin to analyze data that is gained by sensors to predict operation problems, performance and failures. Then that maneuver transfer to the IoT to solve problems and optimize performance. For instant, pump operation is analyzed in ANSYS. Sensors on motor and pump measure operating parameters like pressure, mass flow rate, and vibration. Then based on the results of the simulation, the actuators on the valves control the operation. First in this project, number of operating days until failure is predicted by machine learning algorithm then an anomaly act on the actual system so the sensors show something is wrong but sensors just depict appearance problem and they could not diagnose what is happening inside the system and for example why the system is vibrating. Therefore, the Digital Twin is used to figure this problem out. Information from the sensor transmit to the internet in order to use as boundary conditions for simulation models so the virtual model demonstrate the same symptoms like actual model. The Digital Twin provides facility to analyze what is happening inside the system that was not possible for engineers to understand it by sensors or just simulation. In the next step, the Digital Twin is used to evaluate effect of the changing the conditions on operations. Machine learning algorithms are connected to the cloud to access information from actual product and virtual model (simulation model) to use this information for optimizing the performance, setting control points, scheduling maintenance, sending alerts to operators, and providing reports to management. (White paper, ANSYS.com)

In this work, simulated torque-controlled robots are equipped with ability of transfer a desired disturbance response to unpredicted external forces exerted by the environment on their links. This useful technology is achieved by integration of requirements analysis, rapid prototyping and optimization up to technology transfer.

2.8 Using the Digital Twin in future

Using cyber-physical systems and Digital Twin in industry shows the producers and costumers are not constrained by only mechanical design. Therefore the machines are equipped by servo actuator and control software so switch to the mechatronic machines then provide chance to use flexible manufacturing, energy management, adaptive throughput and machine lifetime value. Saving cost and time in design and manufacturing is the significant point in next generation products.

In recent years, the cost to make dynamic models of multi-disciplinary machines has reduced significantly. By using these new digital technologies in creating prototype and design and manufacturing steps in the project saves huge cost and budgets. So tools to develop this process should be identified quickly.

Digital Twin technology is not only for design process, it can be used for training operator on a virtual model without risk of damage to the system with less cost compare to appropriative training simulator. The Digital Twin can use in parallel with real machine to detect immediately any malfunction or fault in the real system. So the virtual model identifies the source of the problem then prevents serious disturbance and destroy in the real machine.

The machine can perform remotely by using IoT technology so the machine and operator connect to each other through the internet. In addition, it is not just connect to operator; the machine can communicate with the others like customers and even the other machines. The Digital Twin provide accurate and optimize way to analysis and predict the performance and avoid the accident or faults between machines or operators by using the minimal input for controlling. (Goossens, 2017)

3 RESULTS

In this master thesis, the panel repairing line is modeled as a rigid multibody system. Real-time simulation is used to develop the dynamic model of the Cartesian robots in Mevea, while the control system model is developed in Simulink. The purpose of the survey is to control the position and velocity of the Cartesian robot to do the repairing tasks.

3.1 Multibody dynamic systems concept

Multibody system dynamics is a method to analyze the dynamics of the mechanical systems which consist multiple bodies. In order to simplify and decrease computational complexity the bodies are assumed as rigid in multibody system analysis. The distance between two particles in the rigid body remains constant at all times and all configurations.

The multibody system consists rigid bodies, joints and force elements. The role of joints is to connect the bodies and the force is applied on two linked bodies with same magnitude but in opposite direction. In this case the force vector is known as a function of position and velocity of the two linked bodies. The force element is divided to the active and passive force elements. Spring and damper force is the one model of passive force element and actuators are the active force element that are defined by a control law of the position and velocity variables. It is important to know, the force elements do not create kinematical constraints.

Each two bodies are connected to each other with just one joint. In other words, a joint cannot connect more than two bodies. The joints restrict the relative movement between bodies. Each constraint equation omits one movement way. The degrees of freedom of the system is the all possible paths that the bodies in the system can move. If the number of degrees of freedom will be positive number, then the system is kinematically driven. The translational joint limits two motions. The translational joint is the joint between two bodies which translate with respect to each other in one axis. The axis of movement is known as the line of translation. Therefore, there is no relative rotation motion between the bodies. Figure 3.1 shows an example of the translational forces between to slider. (Shabana, 2013, pp. 1,2) (Wittenburg, 2007)

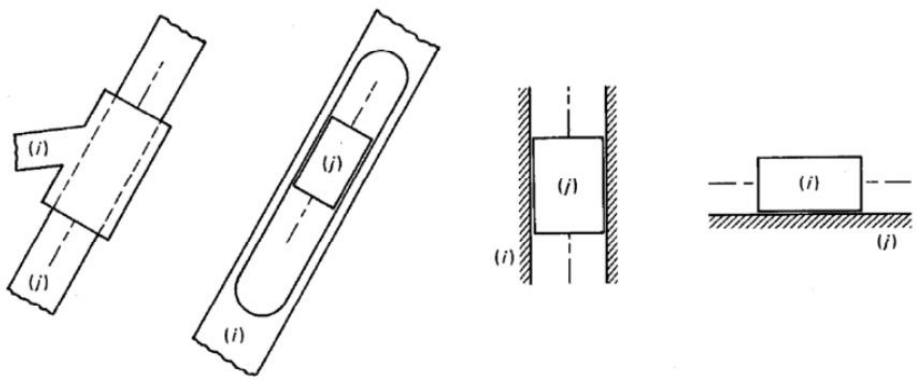

Figure 3.1. Different representations of a translational joint

Mathematical equations describe the behavior of multibody systems. Selecting the proper type of coordinate system is important to form the equations of motion in multibody system. The coordinate systems are used to describe the rigid body point position. The motion of a rigid body in space can be completely described by using six generalized coordinates. The position is described respect to the global frame of reference and body-reference coordinate system. The body reference coordinate system expresses the position of each body point respect to the body and the global frame of reference expresses the translation and rotation of the body.

3.2 Introduce the repairing panel line project

Raute is the one huge company in Finland in making veneer, plywood and laminated veneer lumber. After plywood panels are produced, there are some defects on them which should be repaired before the next production step. Because these faults reduce the resistance of the plywood and quality of them in face to different temperature and impact. The Panel repairing line consists of mainframe to carry all the components and convey to carry plywood panels then running through the line. An intelligent VDA camera is attached at the begging of the line to identify defects on the panels. Four Cartesian robots which are equipped with drilling/machining head or putty/filler head to repair the defect on the panels. These robots travel in lengthwise and crosswise directions. In follow, the operating system is explained briefly:

First, the plywood panels are fed into intelligent VDA camera to identify defects on the panel so the depth, size, and position of the fault are defined for the Cartesian robots to operate on them and repair them. Then the nearest robot runs to the target position with maximum speed then near the target point the speed should be decrease to break speed then robot starts to do operation task with suitable speed which is defined for each task after finishing the operation, robot goes to the next point. This operation is processed in fast speed and robot should move with the panel during operation.

The Cartesian robot moves in 2D plane on the panel repairing line. Moreover, it should reach the position of the defect by one-millimeter accuracy. Cartesian robots should work as fast as possible without missing accuracy. In addition, the reaction force in that speed should not cause damages on the panels and line frame.

Raute is using Cartesian robots for repairing defects on the plywood panels in panel repairing line. In the current panel repairing line, robots are using Festo toothed belt to move between lines in the panel lines. In the current model, the robots are attached to the line then moving 2 directions (lengthwise and crosswise). Because the movement of the lines is limited there is not any probability to collide two robots. In the current model the maximum speed, the accuracy of the Cartesian robots in pointing the area of the defect and the accuracy during operating is acceptable but when the process goes faster because of the flexibility in the belt causes less accurate in high speed.

In the new model, Festo toothed belt is replaced with linear motor. The differences between this panel repairing line and the previous model are: first, the frame of the panel line is fixed and the Cartesian robots move in two directions- crosswise and lengthwise- so in this case the probability of collision between two robots is increased especially in high speeds. It is expected that by using linear motor the accuracy of the finding defect and repair operating on the plywood panel would be acceptable. The aim of the project is to find the maximum speed that the heads go without lose the demand accuracy.

3.3 Using Digital Twin in real-time simulation of panel repairing line

The aim of this thesis is to use the Digital Twin in real-time simulation of the panel repairing line. A Digital Twin is a digital representation of a physical product. It contains the model of the physical product and real-time simulation of virtual product.

The model of the physical object consists Graphic model of the Panel repairing line is created in CAE software. Each part of the line is created separately. Then they are assembled with proper joints which are used between them. Depends on the project, the environment that the model should work in that is designed too. Creating environment is momentous because of the effects on the model processing such as collision between parts or wind effect. Then define the forces that need to move the part of the object then adding control algorithm to control the movement of the parts. Next step is to real-time simulation of the whole system. In order to use the Digital Twin in real-time simulation the data should be updated by the collected data from real world. These data can be collected from actual product by using sensors, then converted to the virtual product to use in real-time simulation. Transmitting data to the Digital Twin is in order to reach the following goals:

- Modify the model of the vehicle.
- Predict the lifetime of each part and whole vehicle
- Provide good information for maintenance and avoid the activities which caused failure in the system
- Analysis parts that is not possible to measure data
- Analysis on the various form of the vehicle for different situations (what kind of motor or hydraulic system is suitable for specific application by considering energy consumption and depreciation.)

Henceforth, updated data from Digital Twin is transferred to the real system to boost the efficiency of the system, reduce time and cost of production.

Figure 3.2 demonstrates the block diagram of using Digital Twin in product development. In the first phase the system dynamics is modeled that includes physics-based multibody dynamic simulation, dynamic equations of the system and system dynamic then in the second phase, the task planning is defined for the system as an input then the motion of the system is simulated to get the proper value for properties of the motion. Therefore based on the outcome of the simulation the virtual model is improved or developed.

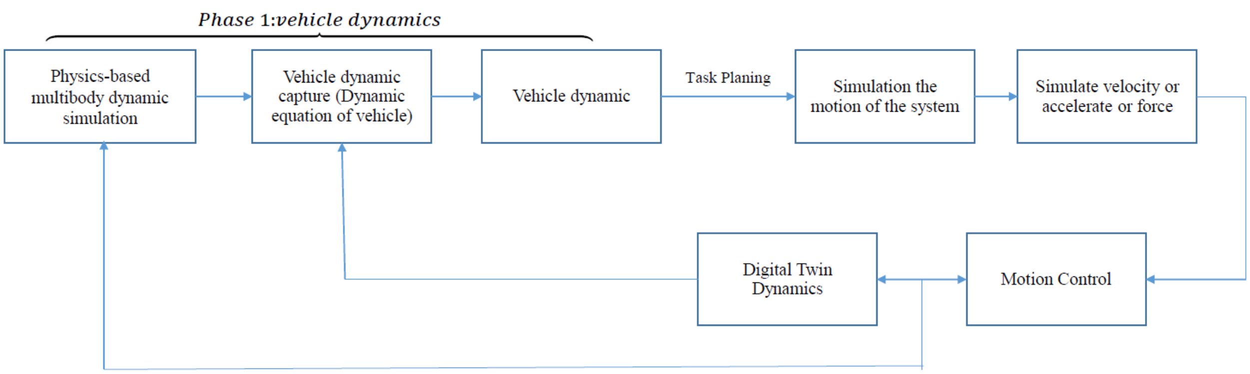

Figure 3.2. A block diagram of using the Digital Twin in Panel repairing line

Figure 3.3 illustrates the flowchart of using Digital Twin in the same procedure. According to the flowchart the initial data and the results of the simulation are transfer to the virtual model and physical model trough the cloud. This facility provides the access for engineer and customer to custumize the product. The flowchart shows the interconnection between the physical and virtual products.

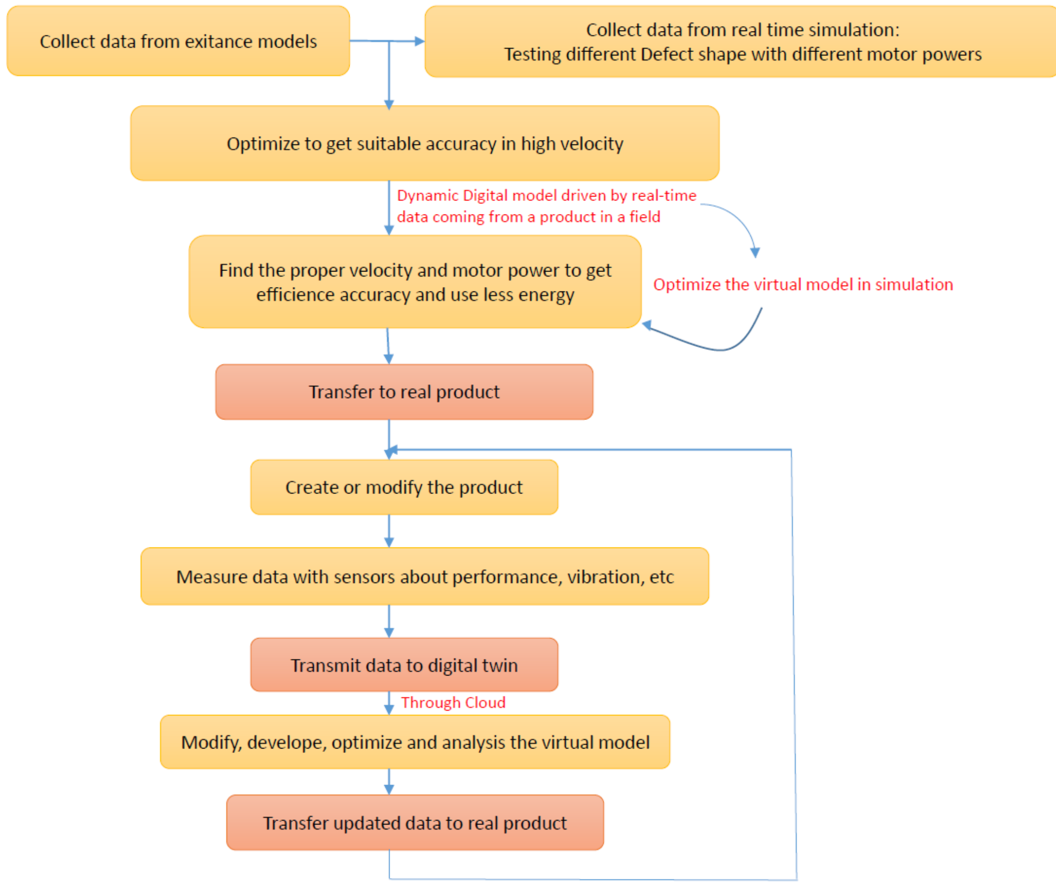

Figure 3.3. A flowchart to use the Digital Twin in Panel repairing line

3.4 System modelling in Mevea:

In this project, four Cartesian robots are working on the repairing panel line. Two first robots are equipped with drilling/machining head and those machine defects open. Two rest robots are equipped with the different kind of dosers and those fill up recognized and machined defect with putty/filler. Dosers are working with pneumatic system. The Cartesian robot is the single axis robot with just translation movement in two directions. Siemens linear motors are used in new model of Cartesian robots to move in two directions. Linear motor with number 1FN3600-4WD30-0BA1 is used to move in lengthwise and the linear motor that is used for moving in crosswise direction is 1FN3300-3WG00-0BA1. The properties of these linear motors are described in table 3.1.

Table 3.1. Properties of linear motors which are used in the Cartesian robots

Linear motor	Max Force (N)	Max Velocity at Max force (m/s)	Rate force (N)	Max Velocity at rate force (m/s)
1FN3600-4WD30-0BA1	13800	1,866	5220	4.23
1FN3300-3WG00-0BA1	5170	6,383	1840	13,93

3.4.1 Concepts of simulation work

This thesis is the first step of simulation work of the panel repairing line. In this new model the Festo toothed belt is changed with linear motor. The goal of this project is to find the maximum velocity that the robots can run and work on convey with demand accuracy. So in the first step the simple model is used that means all parts assume as a rigid body, the friction between the parts is neglected, the Cartesian robot is working as a single axis robot, robots collide with each other and with frame and bodies move in only one direction so no rotation in the parts.

3.4.2 Multibody dynamic system

Figure 3.4 shows a multibody dynamic model of panel repairing line that consists three bodies those are shown in figure 3.5-3.7: frame, carriage part in z-direction and carriage part in x-direction which these carriage parts form a Cartesian robot and plywood panel. The y-axes of the global coordinate system is in gravity direction so the movement of the parts is in x and z direction. In figure 3.8 the coordinate systems are shown on the frame, the green axes is y axes, the red one is the x-axes and the blue one is the z-axes. In this figure, the A coordinate system is the global coordinate system, B is the coordinate system for translational constraint between frame and carriage-z and the C is the coordinate system for translational constraint between frame and plywood panel. This coordinate system is used in the other parts for defining the center of mass and the constraints and forces.

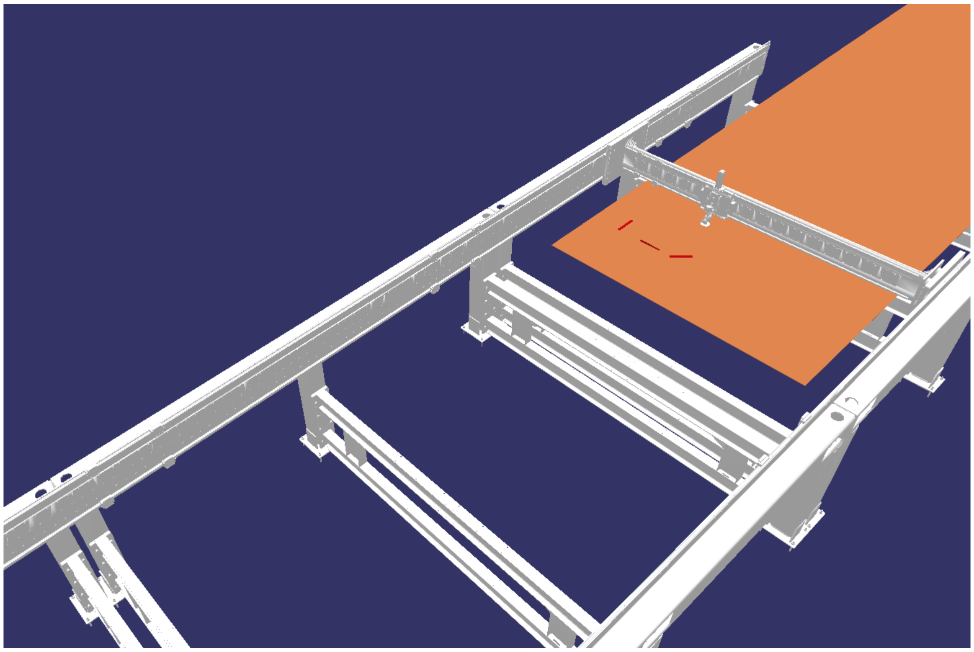

Figure 3.4. Model of panel repairing line in Mevea Solver

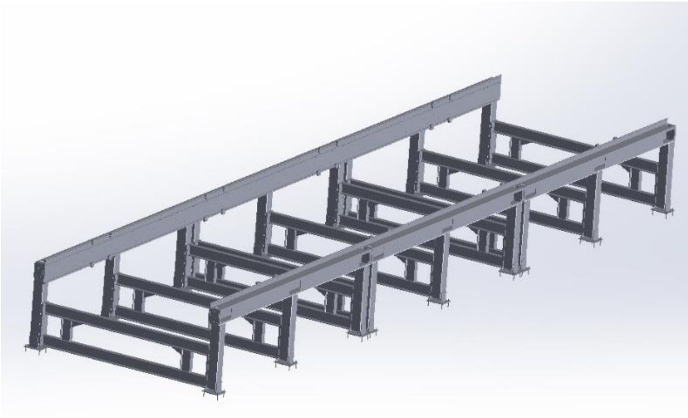

Figure 3.5. Frame

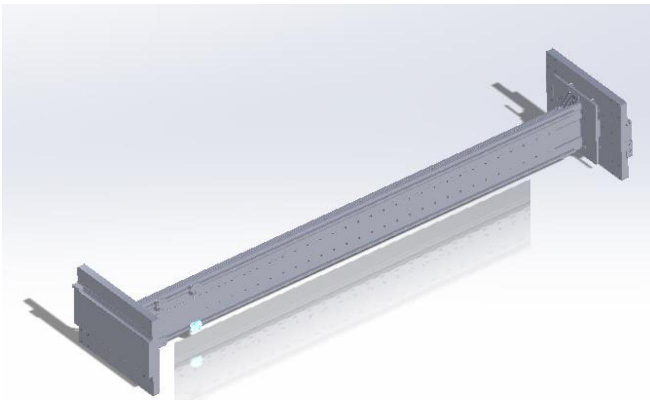

Figure 3.6. Carriage part in z-direction (Carriage-z)

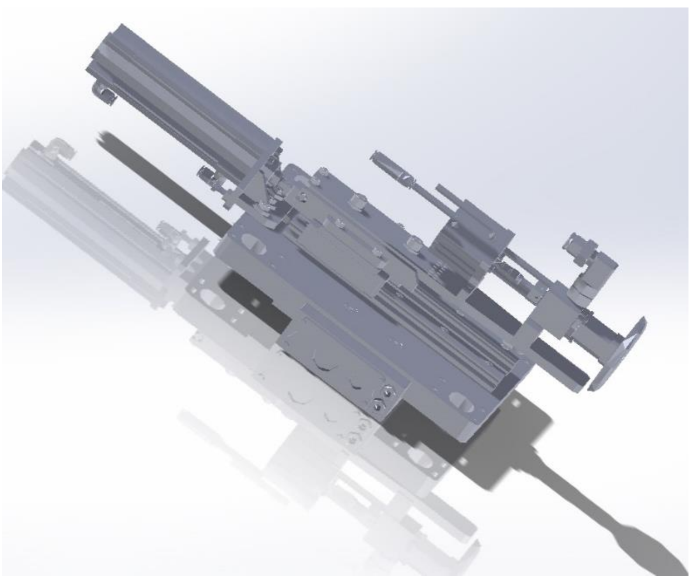

Figure 3.7. Carriage part in x-direction (Carriage-x)

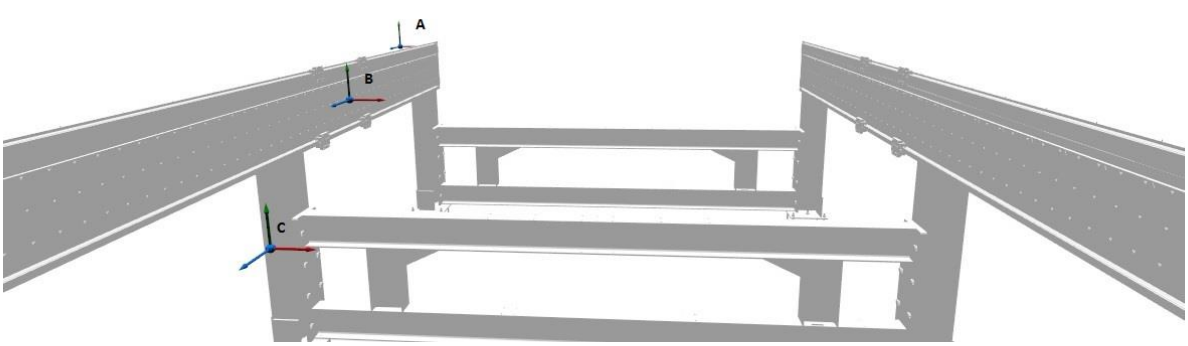

Figure 3.8. The global and local coordinate systems on the panel repairing line

The carriage part in z-direction moves in lengthwise and carriage part in x-direction moves in crosswise. So the joint between frame and carriage part in z-direction is translational joint and carriage part in x-direction is connected to the carriage part in z-direction by translational joint. In addition, the panel is moving in z-direction so there is a translational joint between plywood panel and frame. In summary, figure 3.9 shows the tribology tree of the repairing panel line.

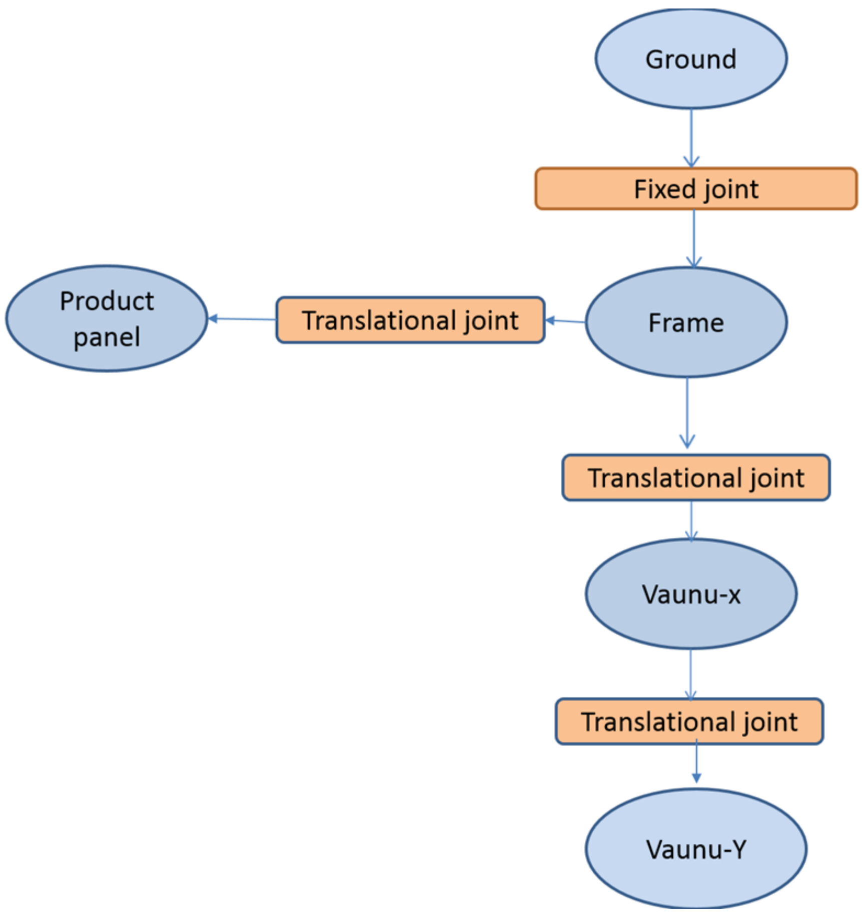

Figure 3.9. Topological tree of the panel repairing line

Tables 3.2 and 3.3 show the body and properties of the body such as the mass, moments of inertia, location of center of gravity respect to the frame and location of center of mass.

Tables 3.2. The properties of parts of the model

name of part (body)	Mass (kg)	Center of Gravity (m)	Rotation angel (degrees)
Frame	8892,6162	x -1,750	X -89,992
		y -,382	Y 0
		z -,0568	Z -90,056
Carriage-z	483,09	X 0,01836	X -89,987
		Y -,002782	Y -1,822
		Z 1,725	Z -89,962
Carriage-x	39,4273	X -,0061381	X 89,924
		Y ,0042621	Y -7,553
		Z 0	Z 0,478

Tables 3.3. The moments of inertia of the parts of the model

Part	Moments of inertia (kg.m^2)		
Frame	I_{xx} 179442,9	I_{xy} -4758281,5	I_{xz} 148,12982
	I_{yx} -4758281,5	I_{yy} 203031,12	I_{yz} 24,931266
	I_{zx} 148,12982	I_{zy} 24,931266	I_{zz} 0,28604605
Carriage-z	I_{xx} 912,05025	I_{xy} -0,14611043	I_{xz} -0,59374553
	I_{yx} -0,14611043	I_{yy} 916,64228	I_{yz} 0,18118327
	I_{zx} -0,59374553	I_{zy} 0,18118327	I_{zz} 14,805109
Carriage-x	I_{xx} 0,39357827	I_{xy} 0,07793038	I_{xz} -0,0032214337
	I_{yx} 0,07793038	I_{yy} 0,97098756	I_{yz} 0,00013313057
	I_{zx} -0,0032214337	I_{zy} 0,00013313057	I_{zz} 0,76048727

The frame is fixed to the ground because of no movement for the frame is needed so the degree of freedom of the frame should be zero. Each Cartesian robot consists of two carriages. One carriage which moves in y direction and another one moves in x direction. Each carriage is one degree of freedom so the Cartesian robot has two degrees of freedom. The carriage which moves in z direction is connected to the frame by translational constrain which can move in z direction (local body coordinate system of carriage and frame are in a same place and z axes is in z direction) and another one is connected to this carriage by translational joint then in this case x axes is in x direction as it is shown in figure 3.10 and 3.11. The markers of the translational joints should be located in the same position and same direction as the direction of the global coordinate system. This direction defines the direction of the movement.

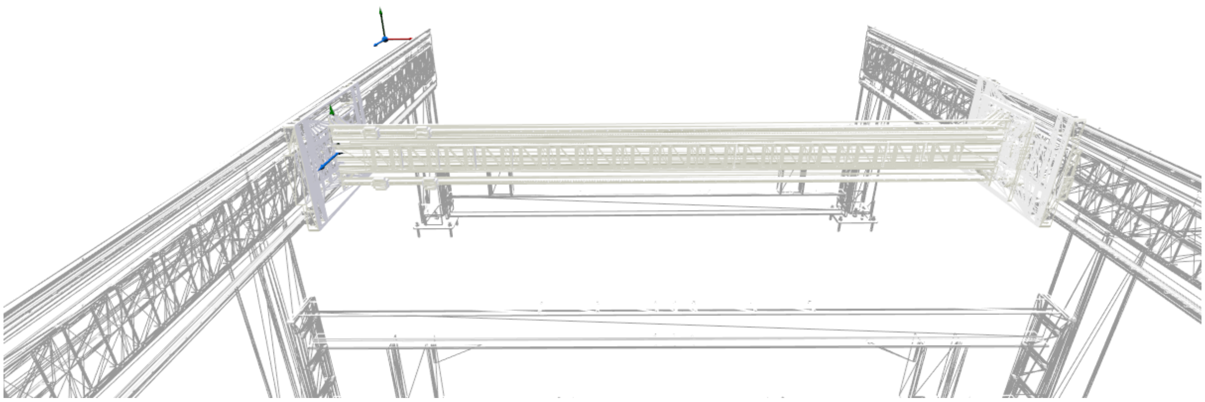

Figure 3.10. Location of markers of the translational joint between frame and carriage-z

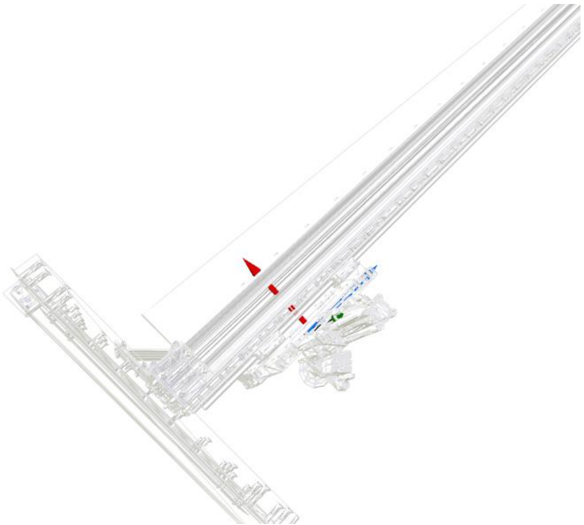

Figure 3.11. Location of markers of the translational joint between carriage-z and carriage-x

In first step of real-time simulation, the mechanism of doser process is modeled by primitive force with zero in initial values to push the head up and down. The force the doser generates is translational force. To avoid collision between heads, one controller will be designed to control the position of the each robot.

The location of the defect on the plywood panel is discovered by intelligent VDA camera then the axes of the location of the panel send to the Cartesian robot. Then robot goes to defined position (x z) by using linear motor then the doser head acts on the defect. The force that doser applies to the surface is defined by translational force with the help of the electrical power. Hence, Electrical power is used to move the Cartesian robot on the frame. Based on the mass of the carriage and the force is needed to move it with desired velocity, two different linear motors are used to move carriage-z and carriage-x.

As it is mentioned in section 3.3, the complete model consists one frame, four Cartesian robots and one plywood panel. All Cartesian robots can move in forward and backward direction. They can travel in whole line so they start running from the begging of the line with no limitation for travelling, except they cannot pass each other therefore they run in the line between the previous and forward robots which are located in behind and in front of it. In simulation model, the collisions between Cartesian robots are defined by using friction between two parts. In viscose friction model, the stiffness is in relation to the object interpenetration. Therefore, stiffness of contact surface and coefficient of restitution are defined to prevent penetration between two bodies.

3.5 Control system

Connect Mevea and Simulink Simulink is used to make a control system to control the movement of the Cartesian robot so the simulated model should convert to the Simulink as a plant then the output of the control system goes to the Mevea again. This method provides real-time connectivity and data transfer between two sub-simulations. Mevea provides the facility to cooperate with Matlab Simulink by Simulink external interface. It is possible through co-simulation loop via TCP/IP Socket interface. The following steps show how to connect the controller in Matlab Simulink with Mevea simulation model.

First step is defining the External Interface in Modeler in Mevea. In model tree open I/O branch then add new Socket interface, figure 3.12 shows the IP and Port that is needed to use in Simulink. Then add SocketSignal in Socket interface branch so signal type and the signal should define here. The output signals are selected from Data sources and the input signals have corresponding signals in I/O (Inputs defined for driving machine). For more information about data source. This part contains the parameters to driving the machine based on defined inputs. Simulink is the server for the Socket IP data transfer from Mevea as a host.

The Simulink contains three S-function blocks: MServerInitializer that is controlling the Time and addressing, MReceivingData consists output block, data to Mevea Simulation Software goes to this block and MSendingData consists input block, data from Mevea Simulation Software comes from this block. By double click on MReceivingData block; the number of outputs are defined in S-function parameters and in MSendingData block, the number of inputs are defined in S-function parameters. If in signal type, AnalogOut is selected, the signal should select from DataSource and if the Signal is AnalogIn, one input is selected for signal. Then start dynamics simulation.

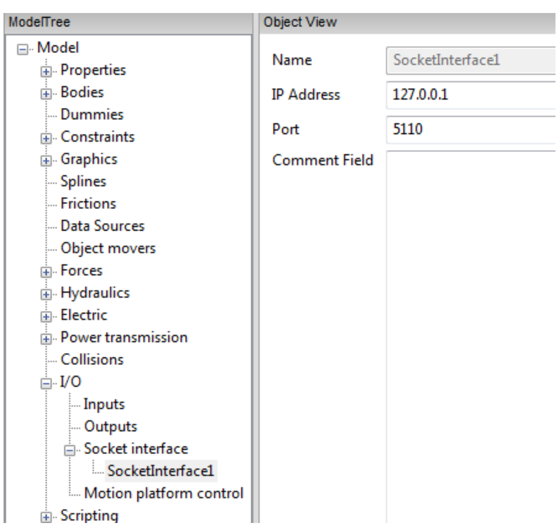

Figure 3.12. SocketInterface section in Mevea

In second step the controller Simulink file should be opened. As figure 3.13 shows the Simulink file that consists MServerInitializer that is used to connect to the Mevea by the same port is defined in Mevea and time constant that should be less than time constant of the Mevea Solver. MReceving data shows the inputs (define by number it means the number of inputs should type here) which should be controlled by controller. Then the next block is the controller and can replace with designed controller by Raute. The last block is MSendingData that is connected to the Mevea therefore it is possible to control the system by running Simulink and driving the simulation.

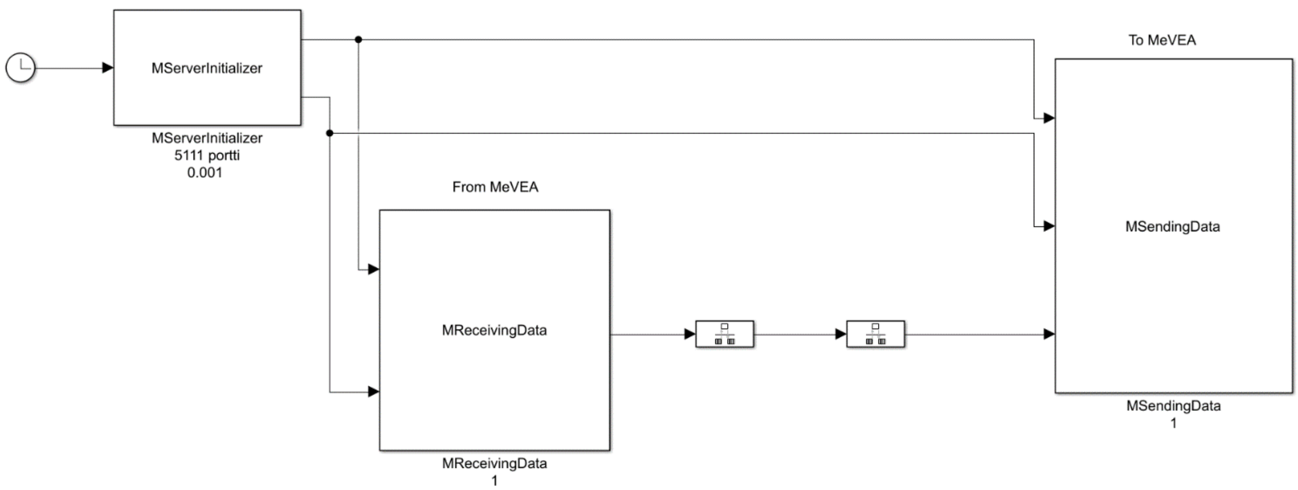

Figure 3.13. Block diagram of the connection multibody model and controller

To adjust the time step in Simulink it is important to consider that the time step in Mevea simulation software must be integer multiple of Simulink fundamental time step that is defined in solver in Simulink. The solver is discrete with fixed-time step. These time steps affect the speed of real-time simulation in Mevea Solver. Therefore, the time step of the Runge-Kutta 4 in Mevea modeler is 0,005 (s) and update frequency is 30 Hz. These values are chosen in order to have enough accuracy in numeric solver and don't lose the real-time simulation. In a similar way, in Simulink the fundamental sample time in discrete solver is chosen 0,01. If this time step would be smaller, converting the data between Simulink and Mevea solver takes more time that means one second in simulation takes 20 seconds in real.

3.5.1 The concept of control system

In the panel repairing line the position of the defect of the plywood panel is recognized by camera then this position send to the robot to go there and do its suitable task for that fault. Dimension of fault and the repairing task are different on each point therefore in the first stage of modeling just one target is defined for the robot. The scenario of the movement of one robot is: the location of the beginning point of fault is in x and y coordinate is transferred to the robot, carriage-z and carriage-x are running to the z direction and x direction respectively with 5m/s velocity then parts should stop in that point then start repairing task by following the path trajectory with 0,25 m/s relative velocity respect to the plywood panel. Figure 3.14 shows the block diagram of the controller that is used to control the movement of the robot. The input of this block diagram is the command position and a controller like PID is used to control it and get the velocity from position to control the position and velocity with together then the output send to the actuator. There is a feedback for velocity and position to compare the output with command position and velocity to adjust the error between output and input close to zero. (SŠabanovic´ & Ohnishi, 2011) (Ohnishi, et al., 1996, pp. 56-67)

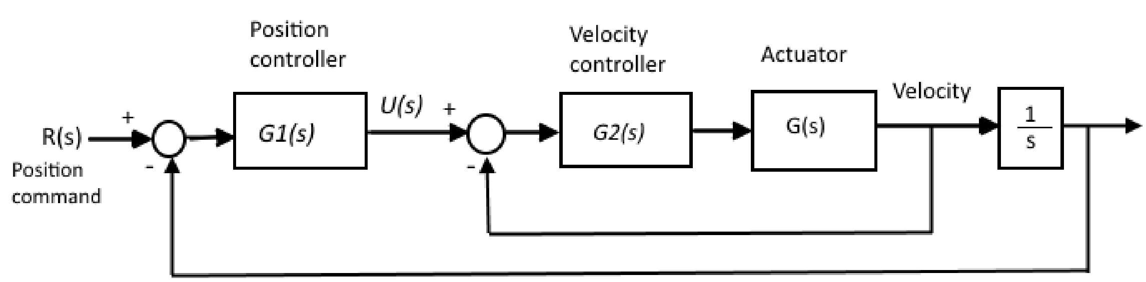

Figure 3.14. Position and velocity control (Dorf & Bishop, 2011)

According to the movement scenario, it is necessary to design a controller, which is control the position, velocity, and force. Motion profiles are used when it is significant to control how to reach the target. These profiles show the velocity varies during the movement from initial position to the target position. In this case the controller acts on the reference velocity and archive to the desired velocity by velocity feedback and in the same time control the position along the route. Cascade P-PI controller is the method when the both velocity and position are important during the travelling time. Trapezoidal velocity profile is one basic profile shape that the first section of the profile is a constant acceleration phase. This phase is continued by a constant velocity phase and the last part of the profile is constant deceleration phase to go to the desired position. The position profile corresponding trapezoidal velocity profile is S-curve profile with linearly increasing and decreasing acceleration. (Karlsson, Sweden, pp. 1,2)

Cascade P-PI controller is used to control the position based on the velocity profile. According to the figure 3.15, in this method the PI controller, controls the velocity then a feedback is used to make sure the output velocity is following the velocity profile. Then the proportion gain controls the positions error with compare to the position that is gained from integration of the velocity. Figure 3.16 and 3.17 demonstrates the velocity and position tracking by cascaded P-PI controller, respectively. (Karlsson, Sweden, p. 4)

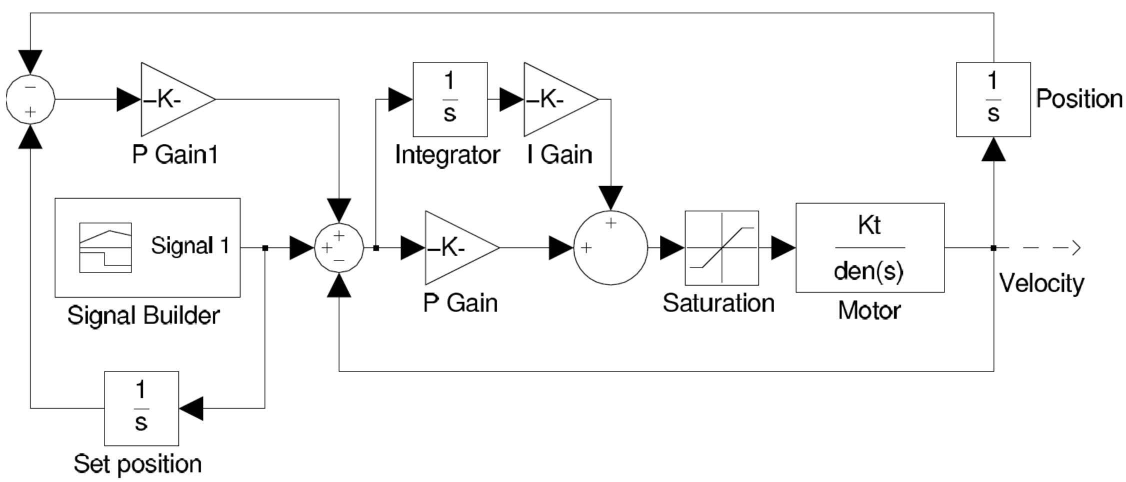

Figure 3.15. Velocity control using a cascaded P-PI controller (Karlsson, Sweden, p. 5)

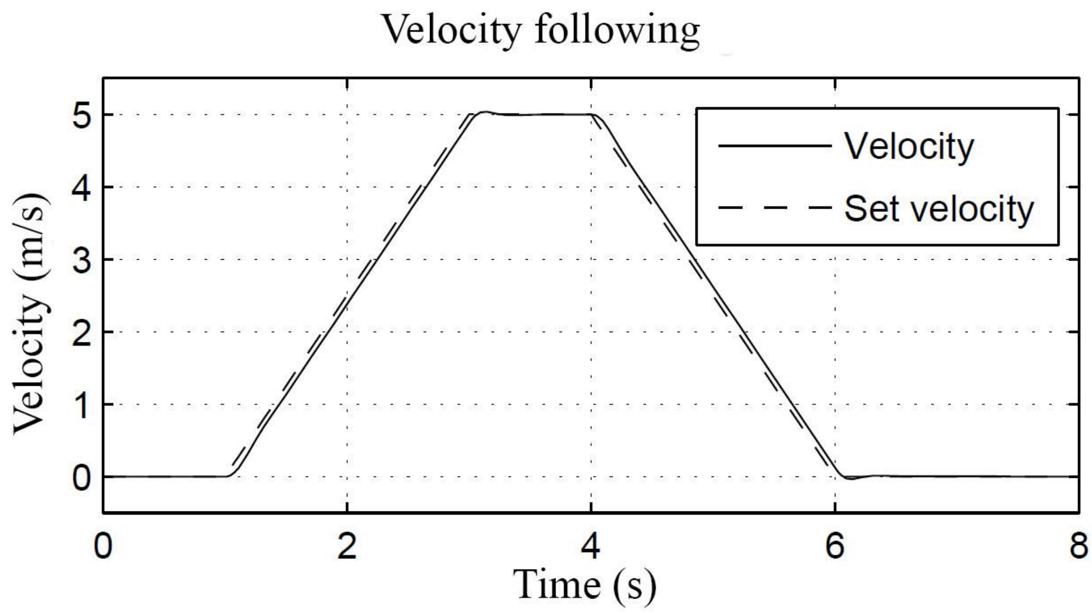

Figure 3.16. Velocity following of a cascaded P-PI controller. The graph shows how the measured velocity follows the velocity profile (Karlsson, Sweden, p. 6)

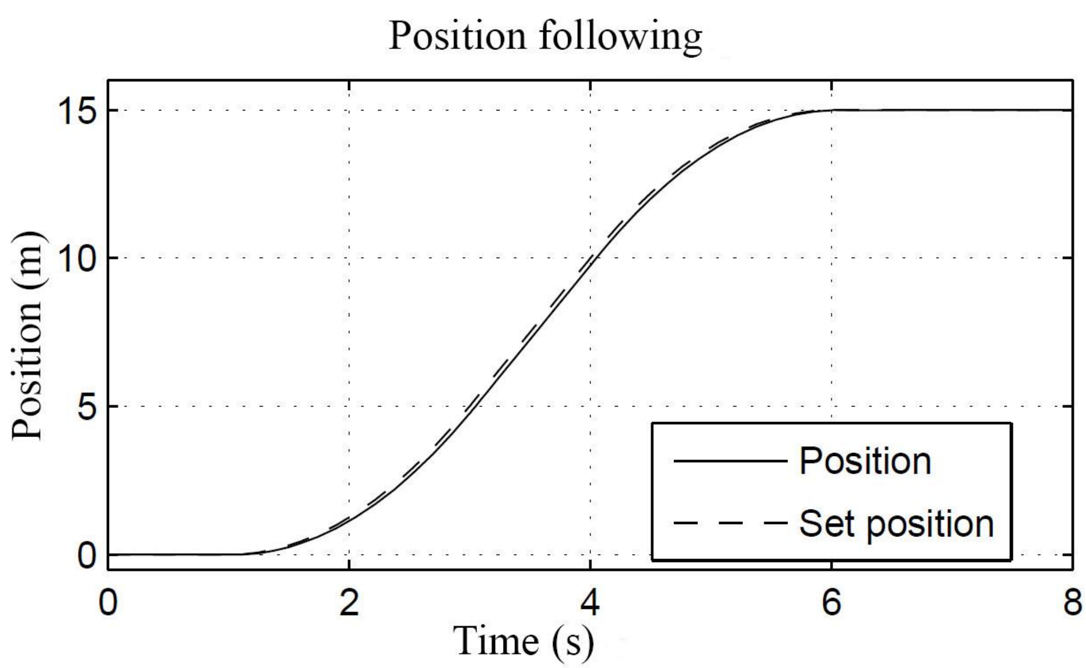

Figure 3.17. Position following of cascaded P-PI controller. The graph shows how the measured position follows the inferred position profile (Karlsson, Sweden, p. 6)

These control system is the basic of the idea of the control system, which should control the movement of the Cartesian robot on panel repairing line. The trust that is needed to move the parts of the Cartesian robots is provided by linear motor. The linear motor is the electric induction motors that are generate force in straight direction of the motion. The difference between linear motor and electric motors is that the stator is unwrapped and the rotor moves through a straight line. Nowadays, linear motors are used in variety machines which move in straight line such as in beltless conveyors for moving panels. In a basic, the linear motor is an AC induction motor that is working by induced electric currents that is generated by rotating magnetic field between the electromagnets that are located in the edge of the motor. The stator that is laid out in the form of the flat coil is known as the primary and the rotor takes the form of a moving platform known as the secondary of a linear motor. The secondary glides are moved by a magnetic field, when the current is switched on.

Therefore, in the real world, the Cartesian robots are moving by changing the force that is generated by linear motor. Changing the current in linear motor causes the desired power. Therefore, the linear motor generates force in order to create the specific velocity profile to reach the desired position. Figures 3.20-3.22 depict the position, velocity and force plots of the Cartesian robot in running in lengthwise direction. As it is shown in Figure 1, the robot starts traveling from the initial position to run for 2 meters distance by 5 (meter per second) velocity. Then there is stop in that point that is the beginning of the defect on the plywood panel. Afterwards the robot is doing the repairing work like machining with 0,25 (meter per second) relative speed related to the speed of the plywood panel. This velocity profile is fed to the control system as an input then by using a proportion gain (P-controller) the required force is created and derivative gain adjusts the accuracy to reach the goal positions. The maximum force that the linear motor can generate is 13800 Newton so the force should not be upper and lower than this value. in the first phase the force increases to about 4×10^4 N to create the maximum velocity then decreases to zero to build the first part of the velocity profile, this force profile during this time is symmetry in opposite direction. Next, the force is boosted again to reach the second velocity then is reduced to go back to zero speed then after got the zero, in order to stay in that position the force is kept in around zero. The block diagram of this controller system and the command velocity profile are shown in figures 3.18 -19.

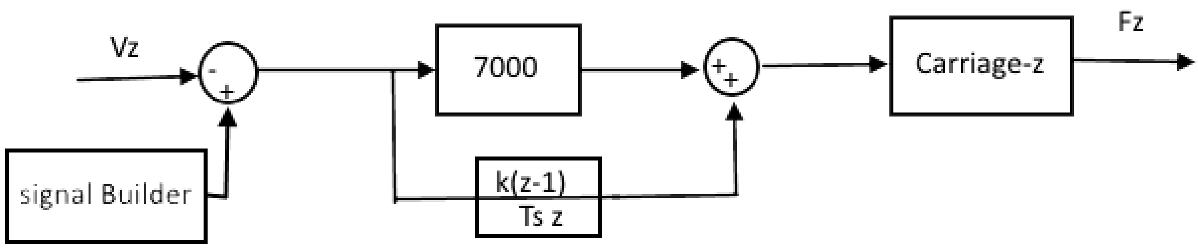

Figure 3.18. The block diagram of the position, velocity and force control of the carriage-z

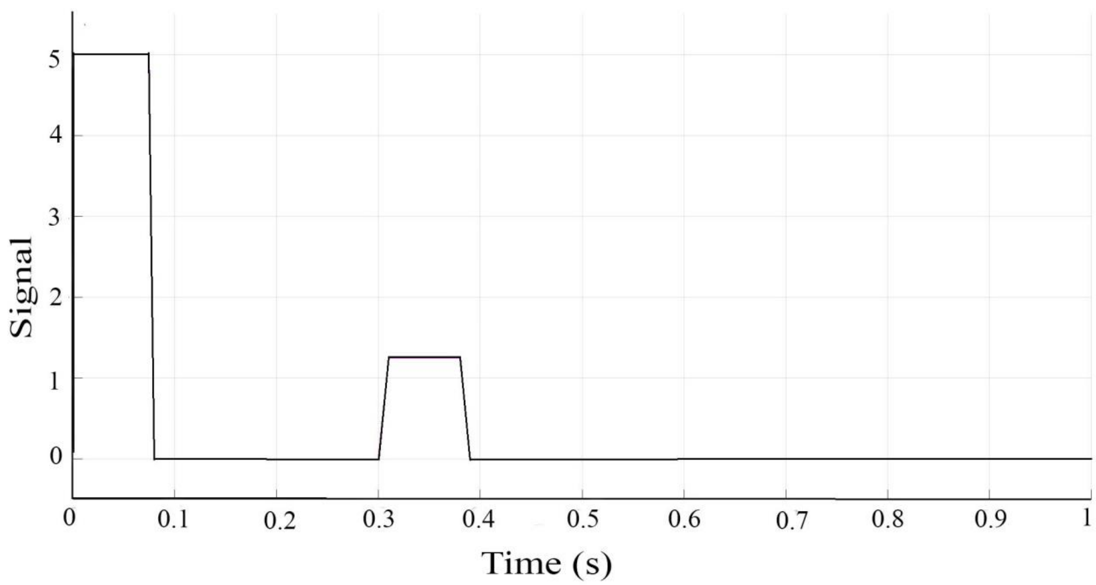

Figure 3.19. Velocity profile input in signal builder in figure 3.17

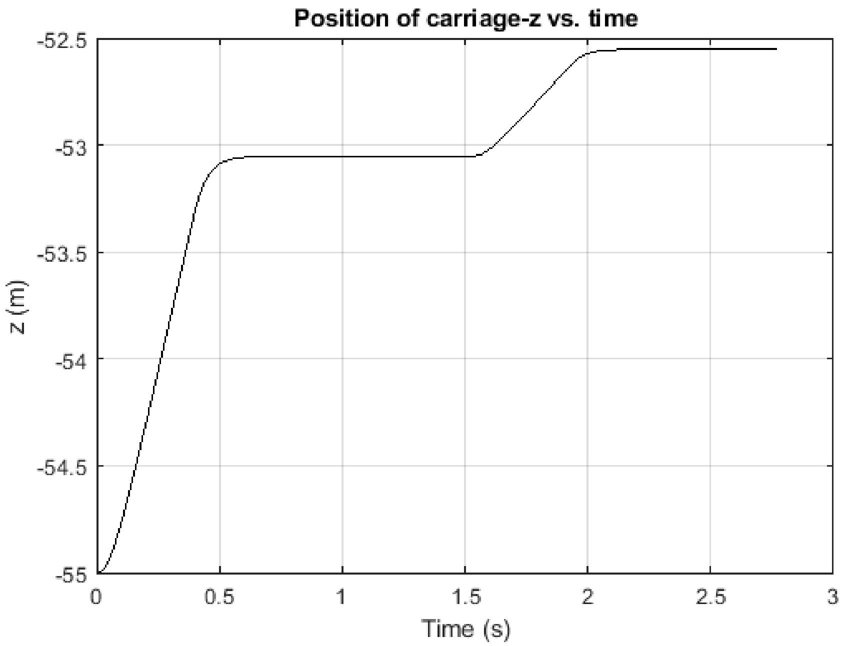

Figure 3.20. Position of carriage_z (Target position:point at 53 m and 52,55 m)

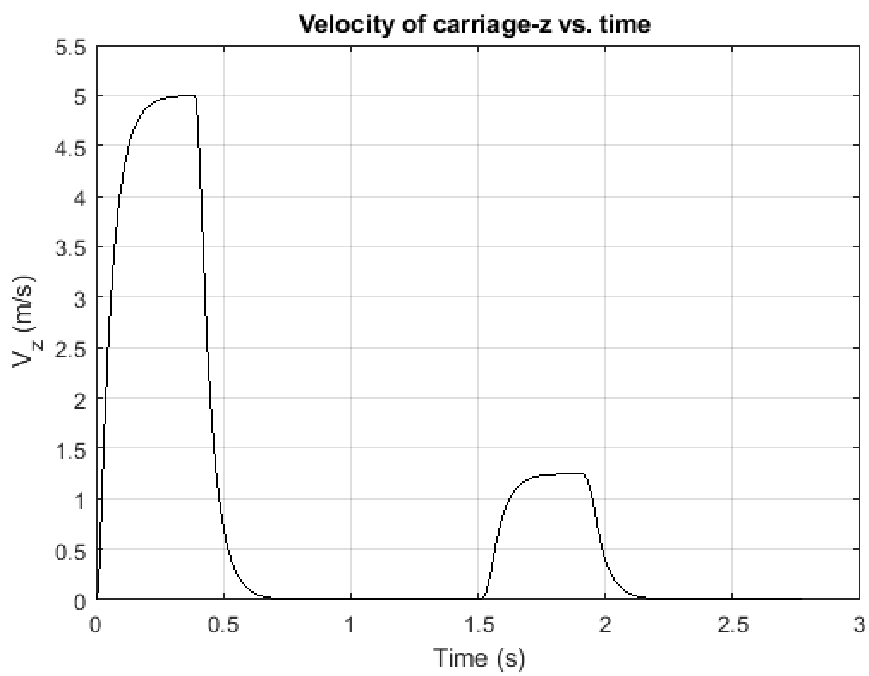

Figure 3.21. Actuator velocity of carriage_z

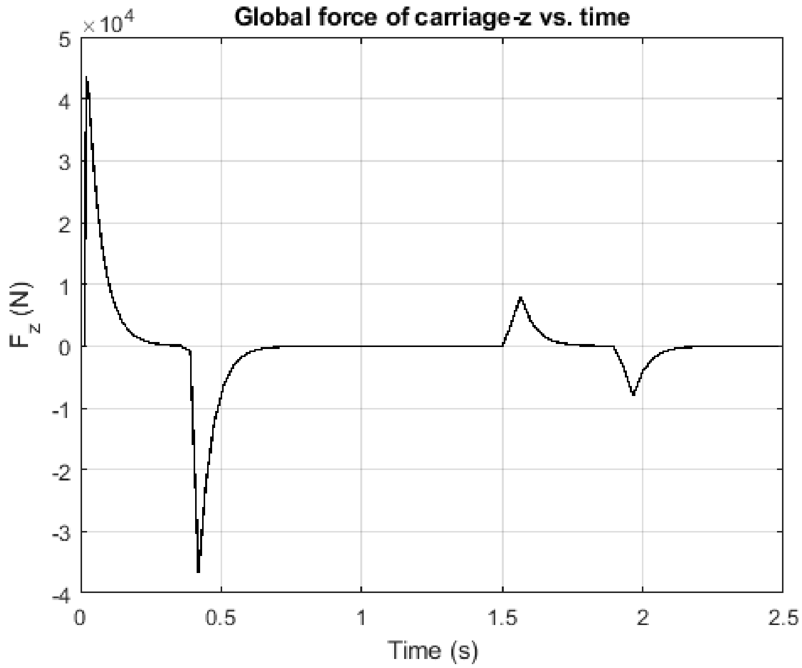

Figure 3.22. Force on carriage_z during moving to the target point.

In the same way, the carriage-x follows the same rule just P-gain is less because the required force is around 5000 (N). The block diagram of this controller system is shown in figures 3.23. In addition, as figure 3.25. depicts, because of the shape and position of the defect that is horizontal (in lengthwise direction) after the robot start to run by 5 (m/s) speed then stop in the point and in order to do the working task it is move by carriage-z. Therefore, the position of the carriage-x should be constant as it is shown in figure 3.27. Figure 3.26 shows the force related to the velocity profile with two peaks to increase the velocity and decrease it.

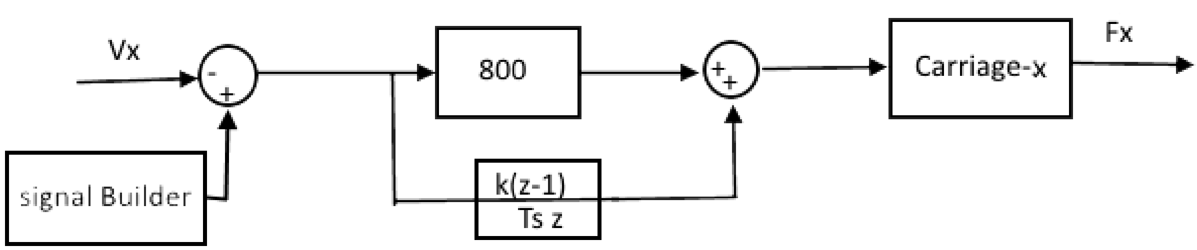

Figure 3.23. The block diagram of the position, velocity and force control of the carriage-x

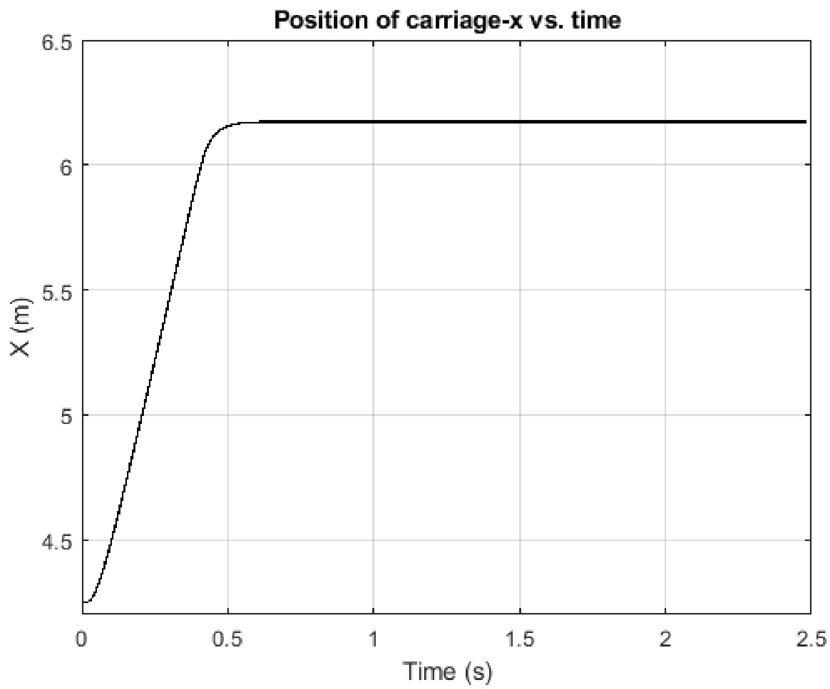

Figure 3.24. Position of carriage-x (Target position: point at 6,25 m then stop)

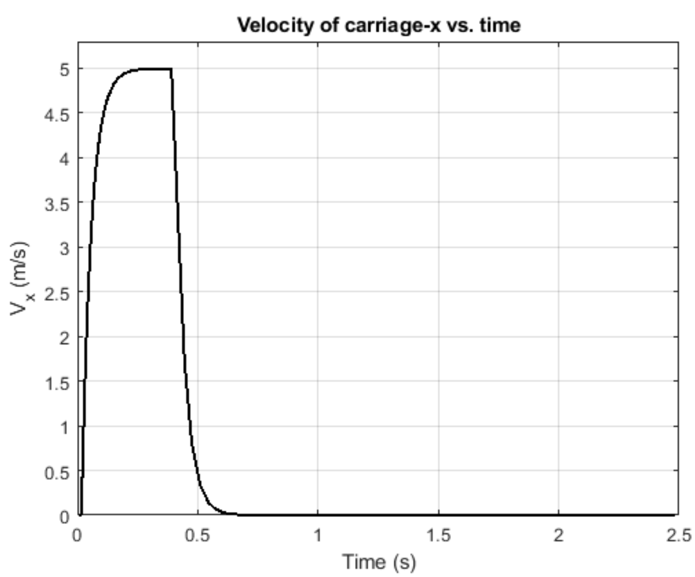

Figure 3.25. Actuator velocity of carriage-x

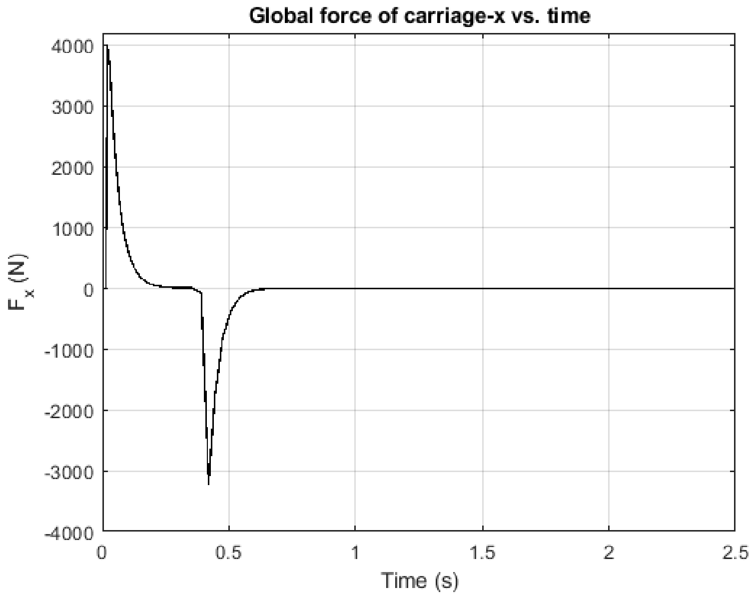

Figure 3.26. Force on carriage-x during moving to the target point.

According to this concept, the movement of the plywood panel is modeled base on this control system. The panel should run with one meter per second speed on convey without stop or changing the velocity. Figure 3.27 depicts the position and velocity profile and generated force are shown in figure 3.28 and 3.29 respectively.

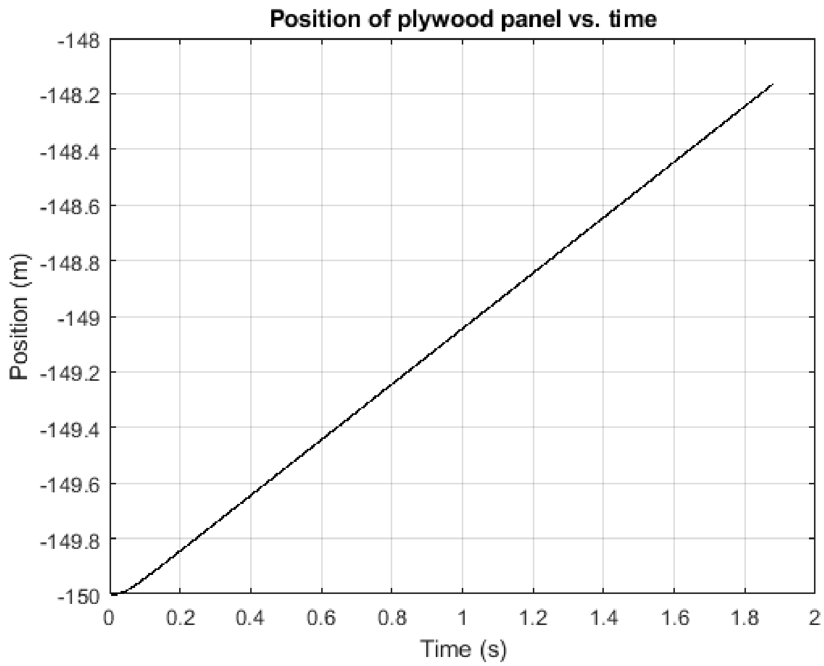

Figure 3.27. Position of plywood panel through the panel repairing line

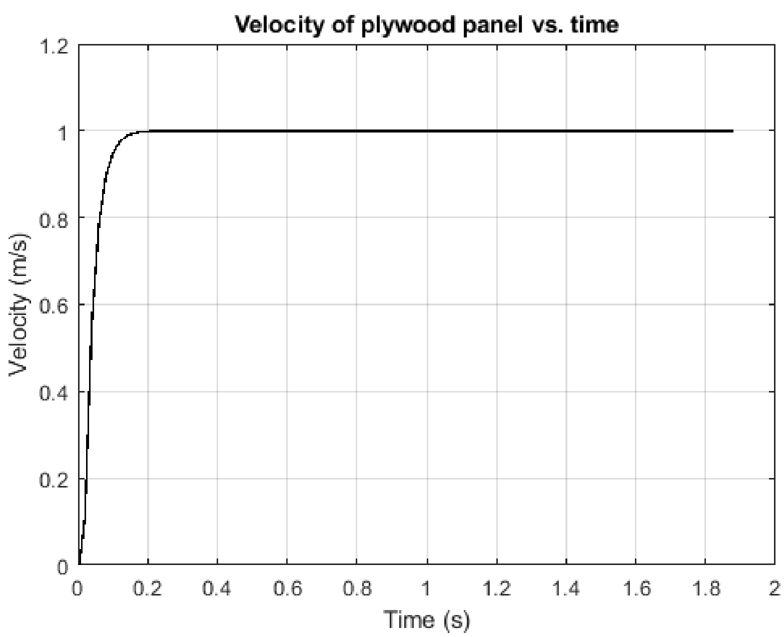

Figure 3.28. Velocity of plywood panel through the panel repairing line

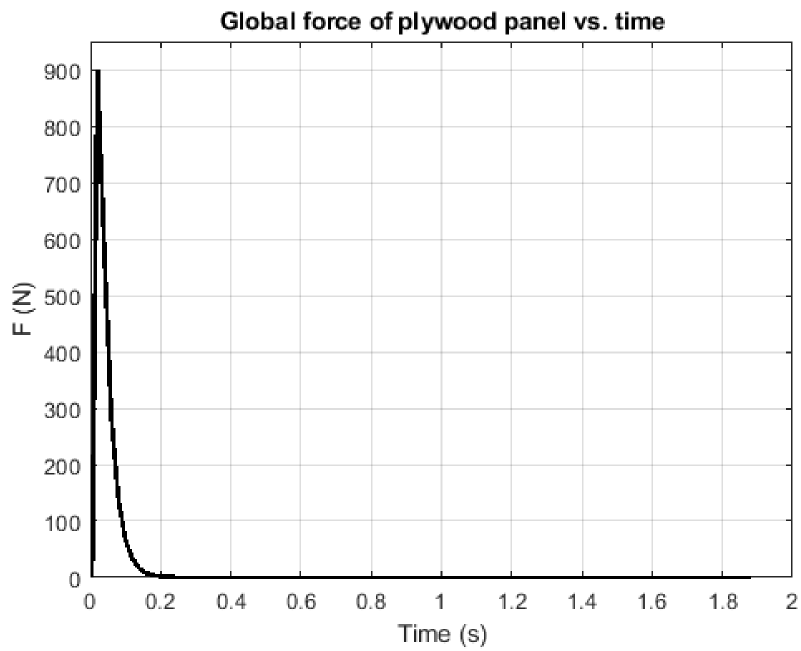

Figure 3.29. Global force of plywood panel through the panel repairing line

This block diagram in Simulink is linked to Mevea by inputs and outputs. As it is mentioned in previous section. MReceivingData block transfer the output from Mevea, so based on the control system it should be the velocity of the part from the real-time simulation therefore it is acting like feedback in the block diagram so the value of the velocity in each time is compared with the value of the desired velocity that is defined in the input. The output of the control system is the force that is generated based on the velocity is needed in each time so the input to the MSendingData is the global force in demand direction. For instant, to control the movement of the carriage-z, in Mevea modeller two data sources should be define: first, the data source of velocity in z-direction, second, data source of global force in z-direction. Then in input section to control the force, the data source of the force is chosen.

3.6 Develop the simulation

In real system, there are variouse shape of defects on the plywood panels in different positions. Therefore, in this stage of survey three different lines with different angles are modelled to guid the Cartesian robots to move to them and do the repairing tasks. Figure 3.30 depicts the shape and position of three defects on one plywood panel.

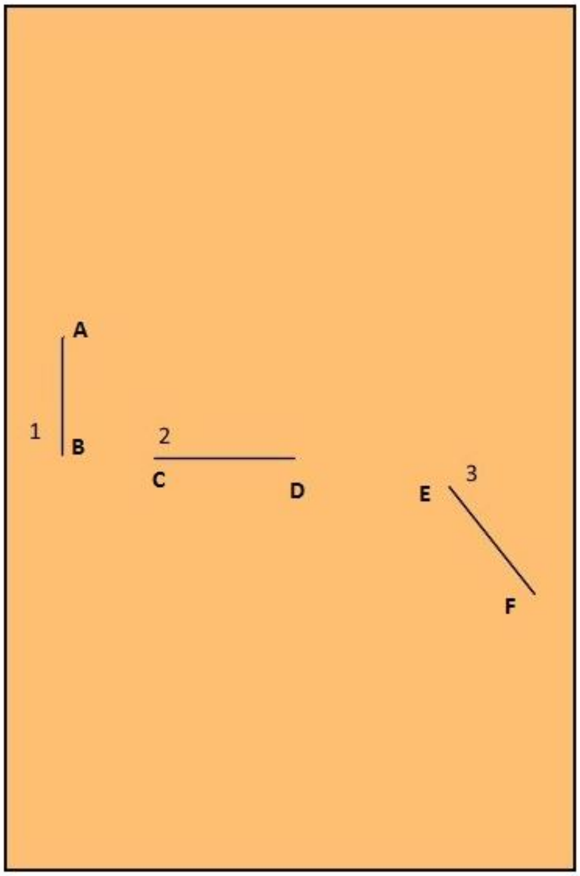

Figure 3.30. Shape of the defects on the plywood panel

The scenario of the advanced phase of the real-time simulation is to define three different shape defects on the plywood panel. The first defect is vertical the second one is horizontal and the last one is the line with the 45 degrees slope. Therefore, the Cartesian should move from initial position goes to the first defect then do the repairing task then immediately increase the velocity and go to the next defect do the repairing task then go to the third position. During these travelling tasks, the panel is moving with constant velocity. The basic concept of controlling the panel in this case is based on the control the position by following velocity profile. Figure 3.31 displays the block diagram of the control system in Simulink. In this case, velocity profile is created by function. This function is working by checking the current position of the part then uses the suitable velocity for that position to reach the command positions. The command positions are fed to the control diagram as a vector of the points. As the part that is running in lengthwise and the part that is running in crosswise are dependent to each other so they should be controlled in the same function. The results of the part which is running in lengthwise is depicted in figures 3.32-34.

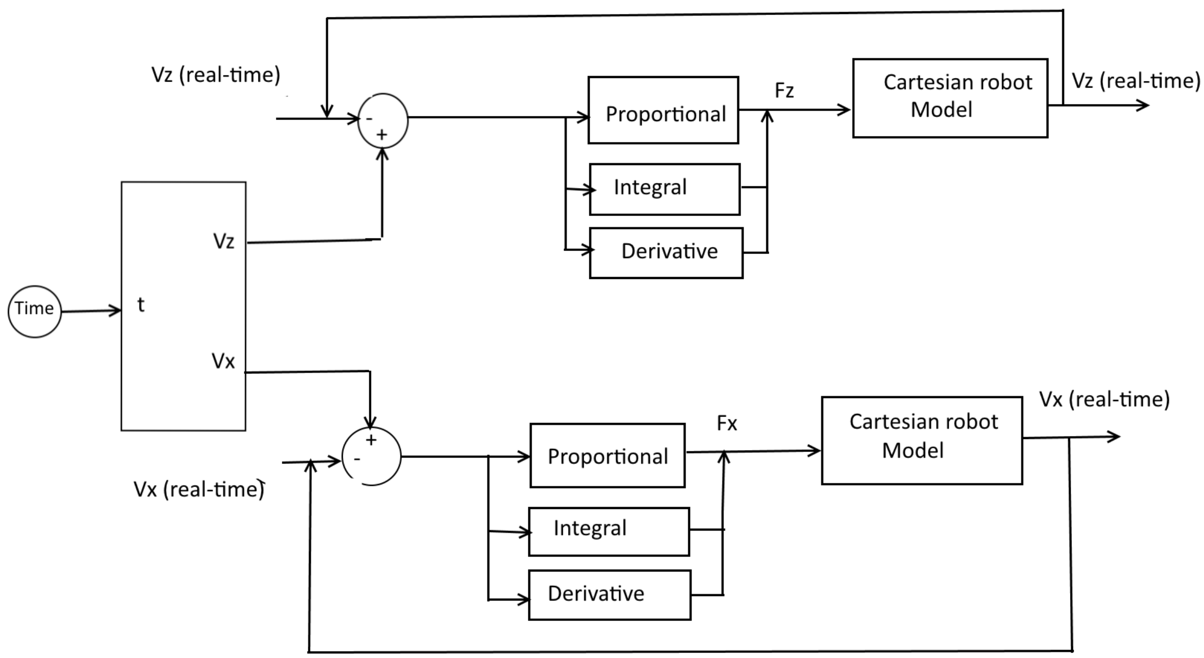

Figure 3.31. The block diagram of the position, velocity and force control of the carriage-x and carriage-z for three defects.

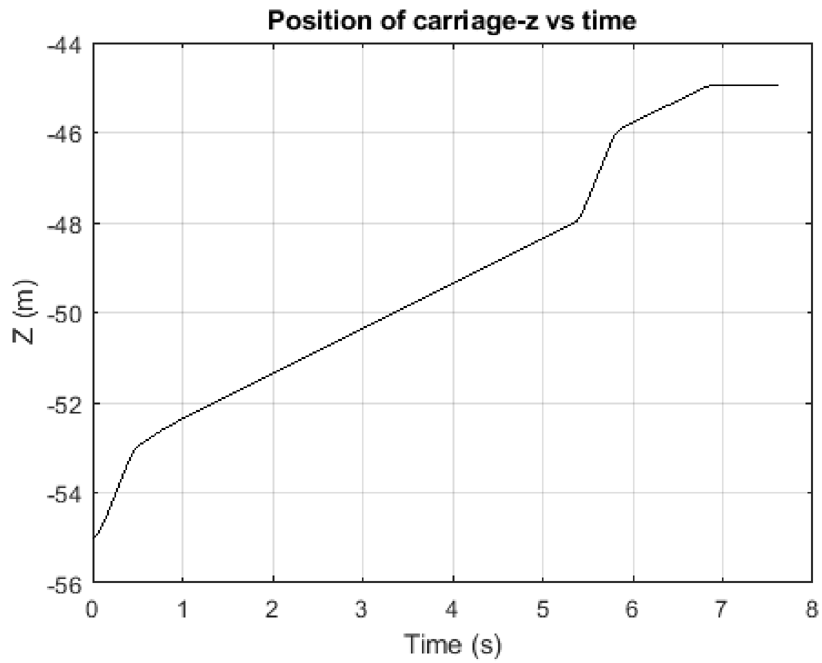

Figure 3.32. Position vs. time for carriage-z (which is running in z-direction) - Target positions: [-53 -52,5 -51,95 -47,95 -45,95 -44,95]

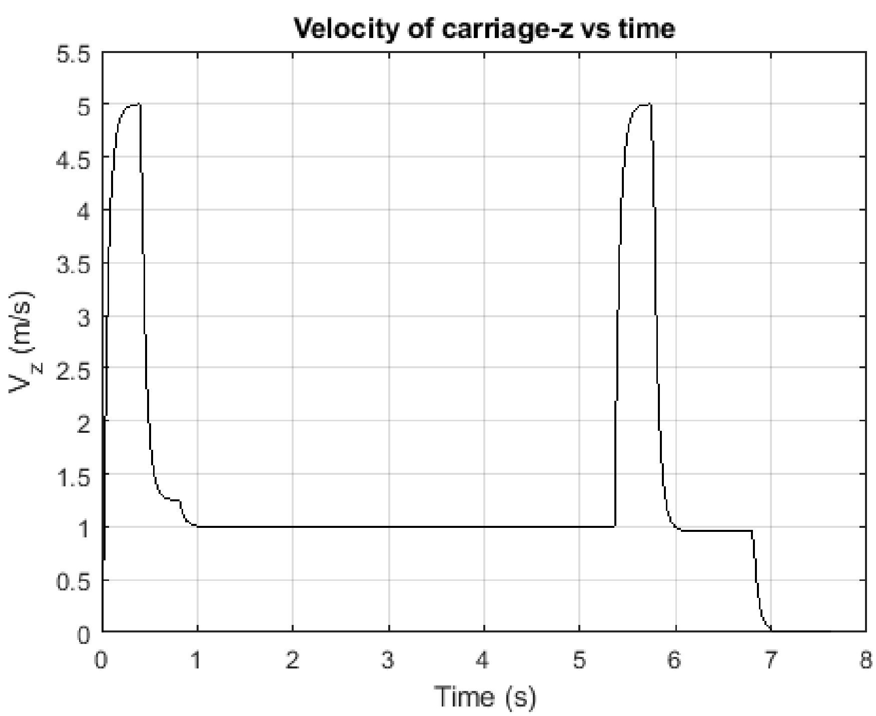

Figure 3.33. Velocity vs. time for carriage-z

According to the velocity profile plot, the robot is running to the first position x (1) with speed 5 m/s then decreases the velocity to around 1,25 and start working for half a meter then the robot should run to the next defect but because this defect is in same z-position so this part should just travel with same velocity of the panel to reach the beginning of the second defect and during working time this part should not change its speed. Then the robot should increase speed to around 5 to move to the third defect so because this defect is a line with 45 degree the velocity of the part should be 0,957 m/s. Figure 3.35 shows the acceleration plot corresponding the generated force.

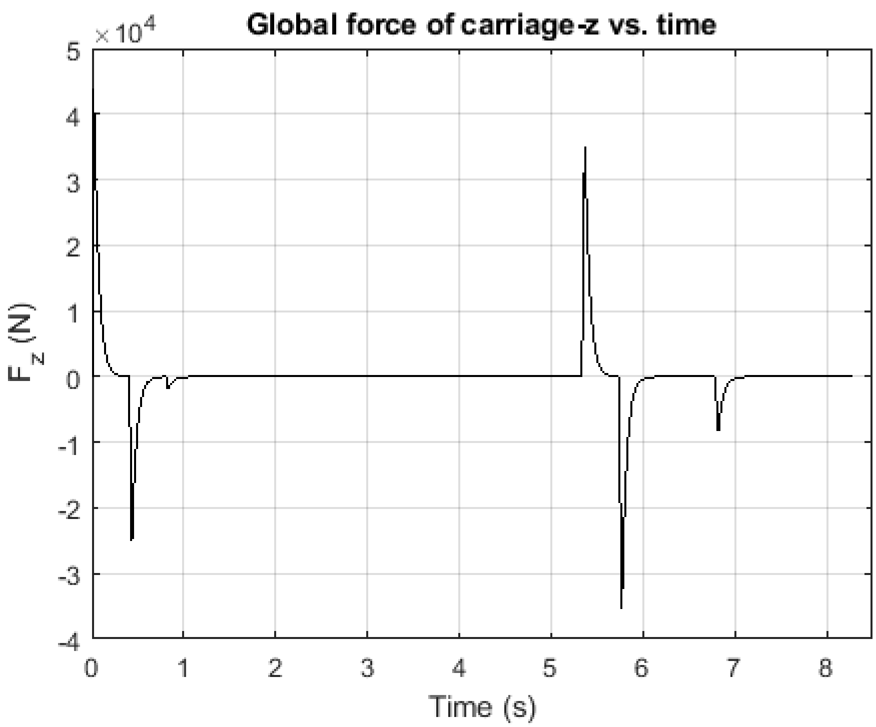

Figure 3.34. Force vs. time for carriage-z

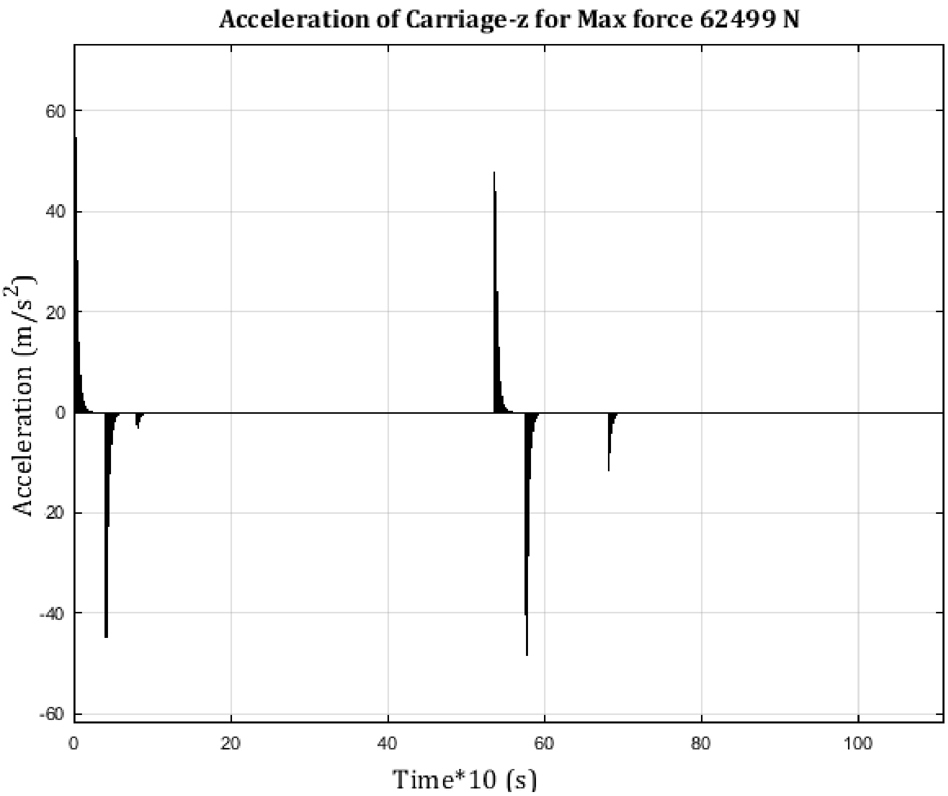

Figure 3.35. Acceleration vs. time for carriage-z

Force and acceleration plots show the amount of generated force to provide the demand velocity. First the huge force is generated then after robot reach the point with 5 m/s speed then the speed is reduced so the force is reduce to the zero. During the velocity in constant the force and acceleration, remain to zero. The behavior of force and acceleration are exactly the same.

The behavior of carriage-x is shown in figure 3.36-39. The carriage-x is running with 5m/s velocity to the first point of the first defect then during working time it should be with zero velocity because the defect is vertical so just the carriage-z should run with 1,25 velocity then it is running to the beginning of the second defect with 5 m/s then working with 0,25 speed then increases the speed to the 5 to go to the third defect and working with 0,957 m/s.

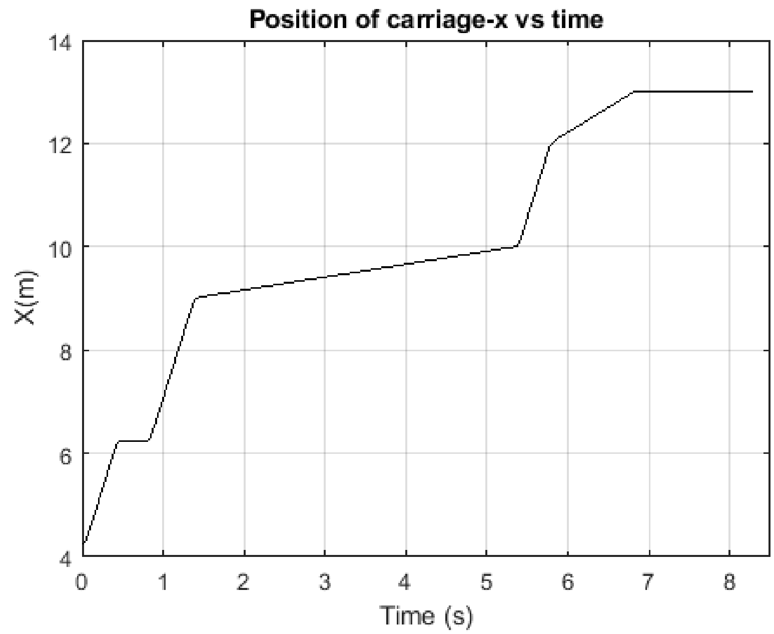

Figure 3.36. Position vs. time for carriage-x (which is running in x-direction)-Target positions: [4,25 6,25 6,25 9 10 12 13]

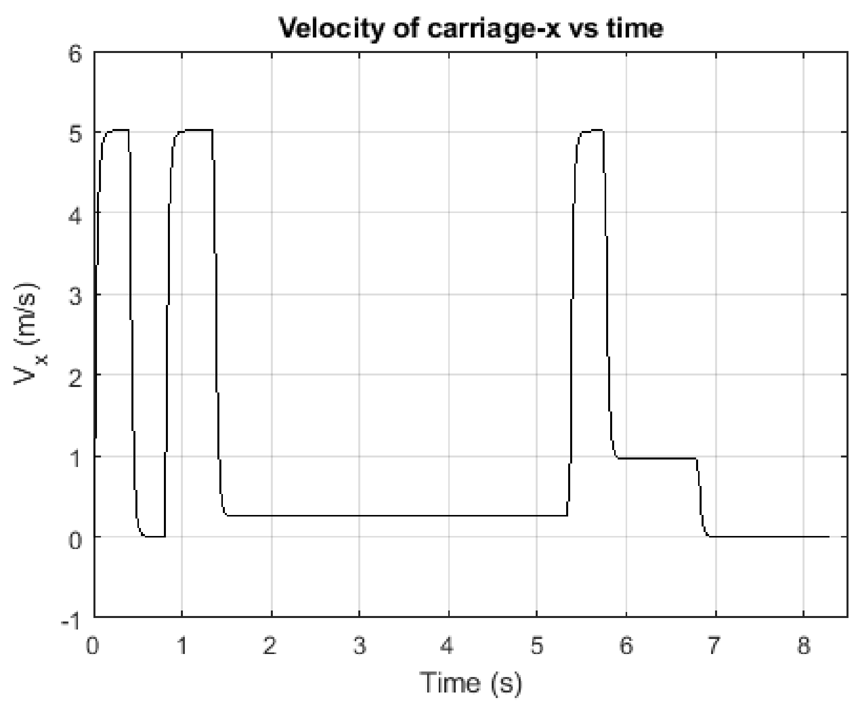

Figure 3.37. Velocity vs. time for carriage-x

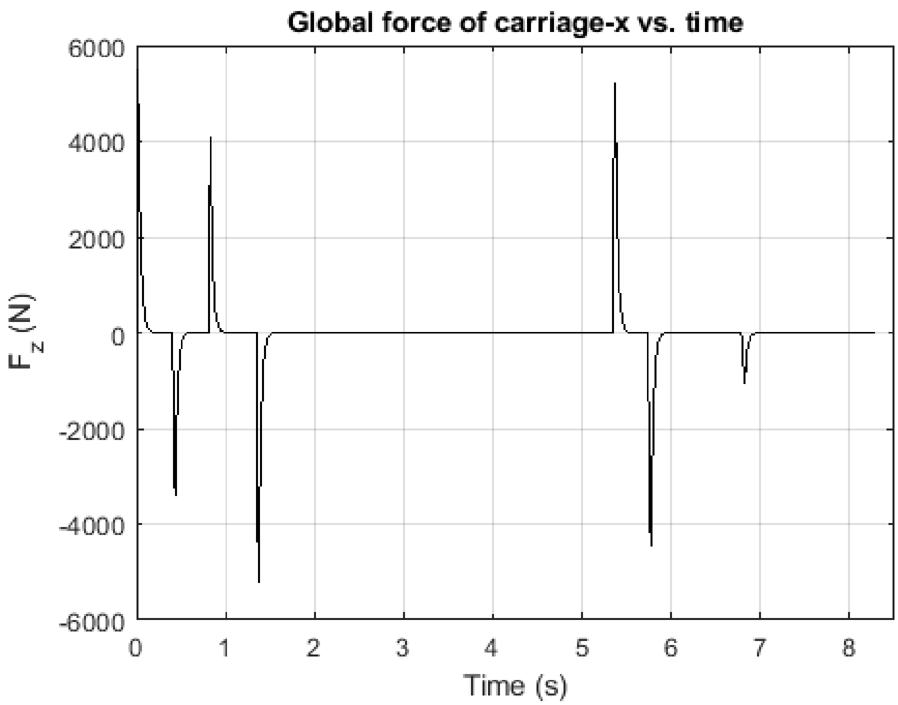

Figure 3.38. Force vs. time for carriage-x (which is running in x-direction)

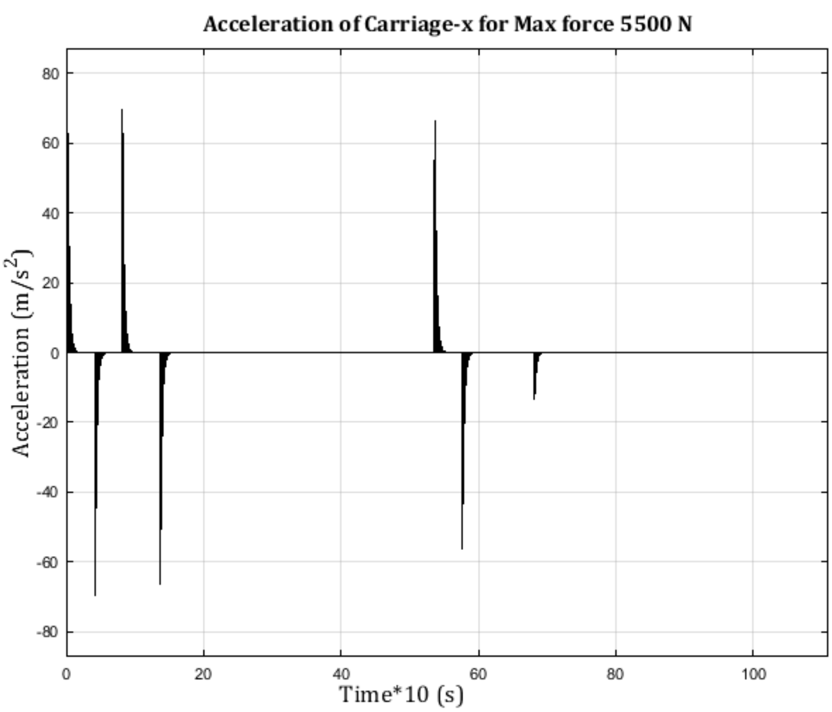

Figure 3.39. Acceleration vs. time for carriage-x

3.7 Analysis results

In this section the accuracy of the position pointing is analyzed in different forces and velocities. Figure 3.37 depicts how the velocity of two parts is synchronized. It is very important to reach the target point in the same time by both part of the robot. For instant, when the carriage-z reaches the beginning of the first defect in z-axis the carriage-x should be exactly in that point in x-axis. Otherwise, the carriage-z should run with 1 (m/s) speed (same speed as panel) until the carriage-x arrives to the point in x-axis. Pursuant to the figure 3.40 changing the velocity in carriage-z is not immediately and need more time. So in a short distance the accuracy to reach the (x, z) axes of the point by two parts in a same time is not enough accurate in carriage-z. Figure 3.41 is the position plot of the carriage-z respect to the carriage-x that shows the curve of the pathway in x-z plane.

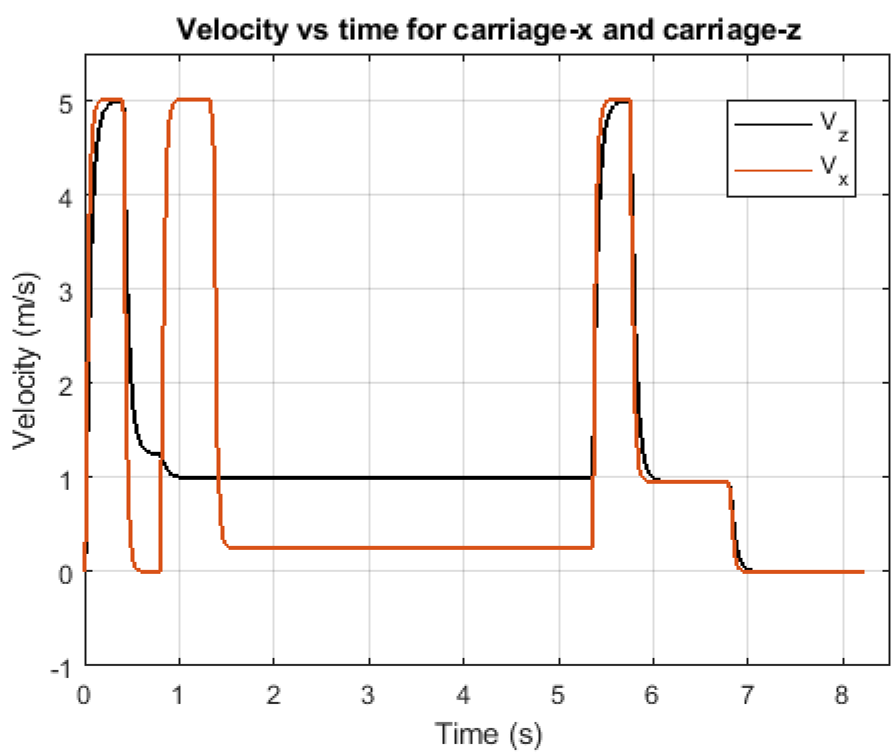

Figure 3.40. Velocity vs. time for carriage-x and carriage-z

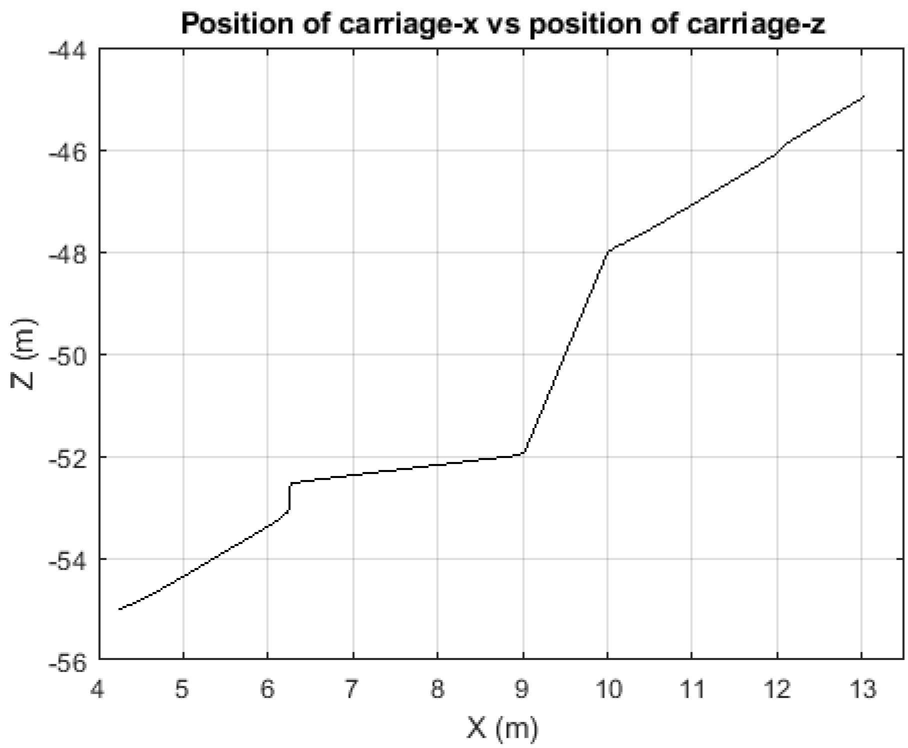

Figure 3.41. Position of carriage-z and Position of carriage-x

In follow, the position error of each part of the robot is shown in different situations. Figure 3.42 and 3.43 illustrate the pathway of each part in real-time simulation and desired pathway. As these plots show the whole pathway is almost the same so the precision in a working way is acceptable. But in another plots the exact error of the parts in the crucial point are analysis. For example the running way is not important but the points in defect curves are very important to reach all points by one millimeter precision.

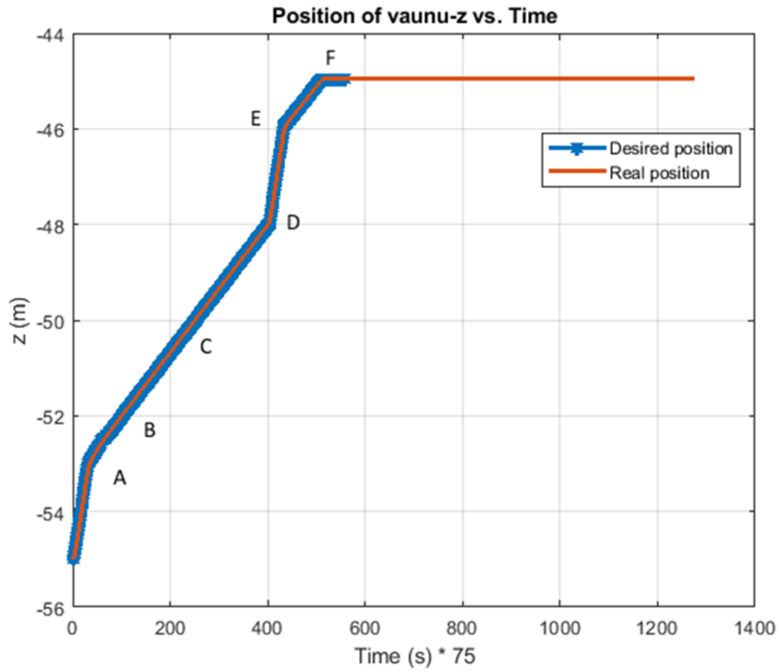

Figure 3.42. Position control of both parts. (Yellow line is the desired positions and blue line is the position of the part (carriage-z)

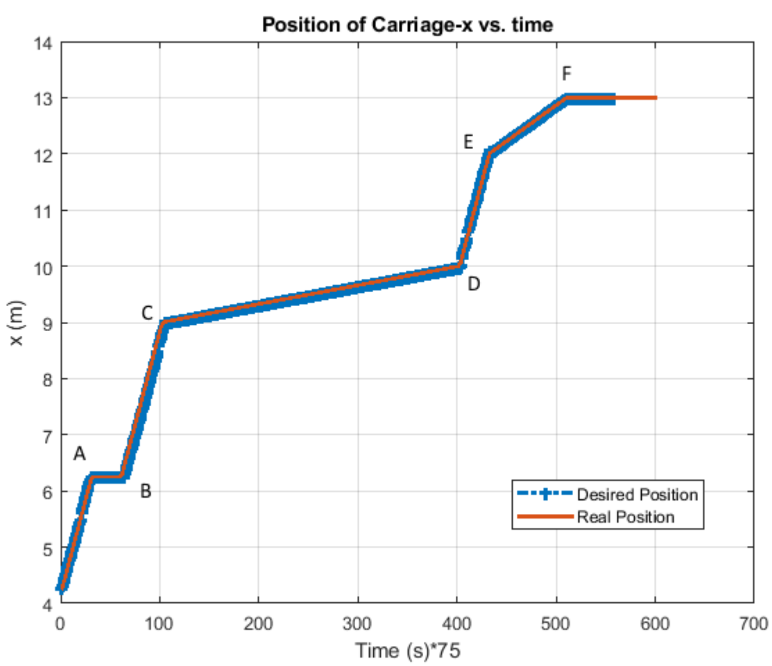

Figure 3.43. Position control of both parts. (Yellow line is the desired positions and blue line is the position of the part (carriage-x)

As it mentioned previous the maximum force that the linear motor generates is not enough for moving carriage-z with five (m/s) with high accuracy. Hence, the position errors in significant points like beginning and ending points of the defect and some point on the defect path. Figure 3.44 and 3.45 represent the position error of carriage-z and carriage-x in different force power respectively.

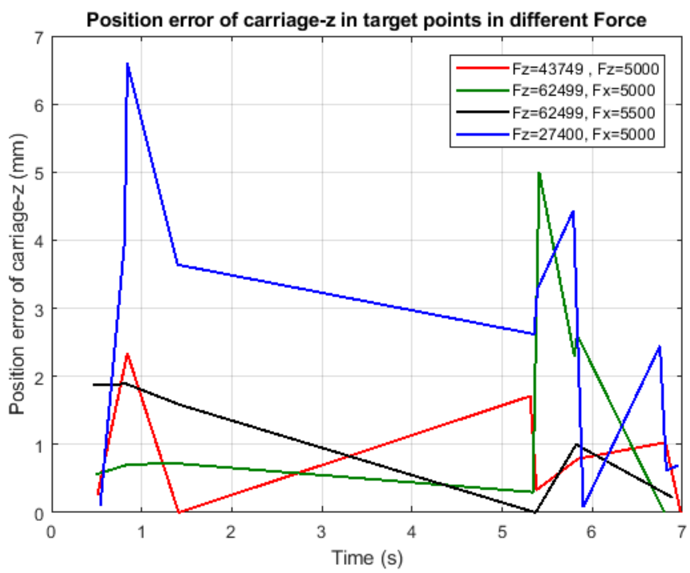

Figure 3.44. Position error of carriage-z in different forces

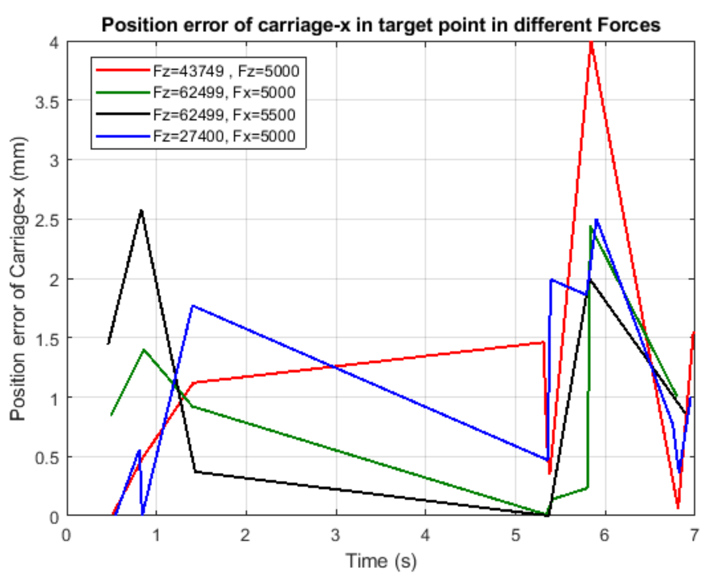

Figure 3.45. Position error of carriage-x in different forces

In the carriage-z, the red and blak lines are almost in less error respect to the other lines. The blue line shows the higher error around 3 to 4 millimeter because the power for movement is not enough to change the velocity in short distance. Based on figure 3.45, the green line present almost 1 millimeter error in most points and red line is the line with highest error compare the others in carriage-x. All in all, by compromise between the results of both plots the best choose is black line or grean line that in bothe the force fo0r carriage-z is the same and only the force in carriage-x is different.

Another analysis is about the maximum runing velocity. These analysises are done on the control system with a P gain that generates force that is gained in last part; because the 27500 N force is not even enough to run more than 5,6 (m/s) speed. Figures 3.46-51 show the position error in pathway of three defects, with speed 5, 8 and 10 (m/s) for both parts of the robot. According to these plots when the velocity is increased, the accuracy is reduced thus it is arount 3 to 4 milimeter in avarage especial in carriage-z and the precision in carriage-x is closer to acceptable value.

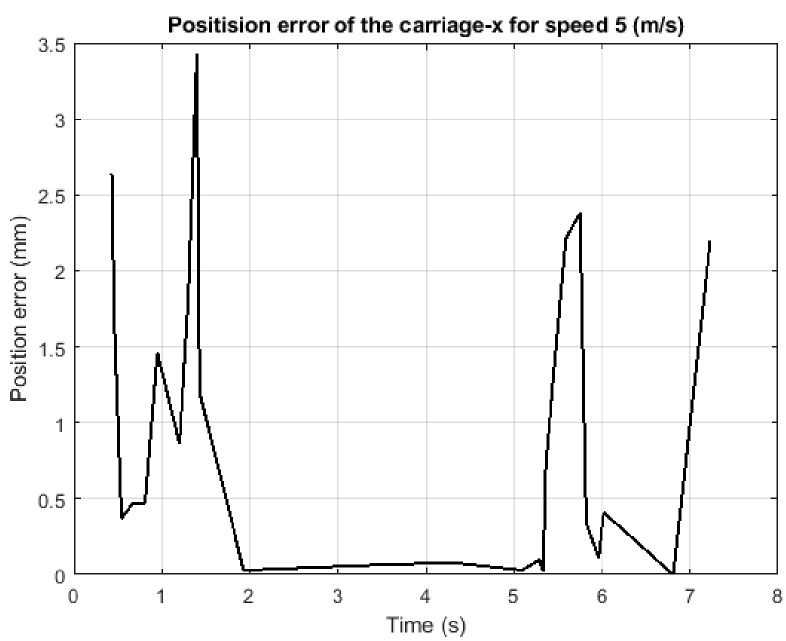

Figure 3.46. Position error of carriage-x in velocity 5 (m/s) with almost Max force 5000 (N)

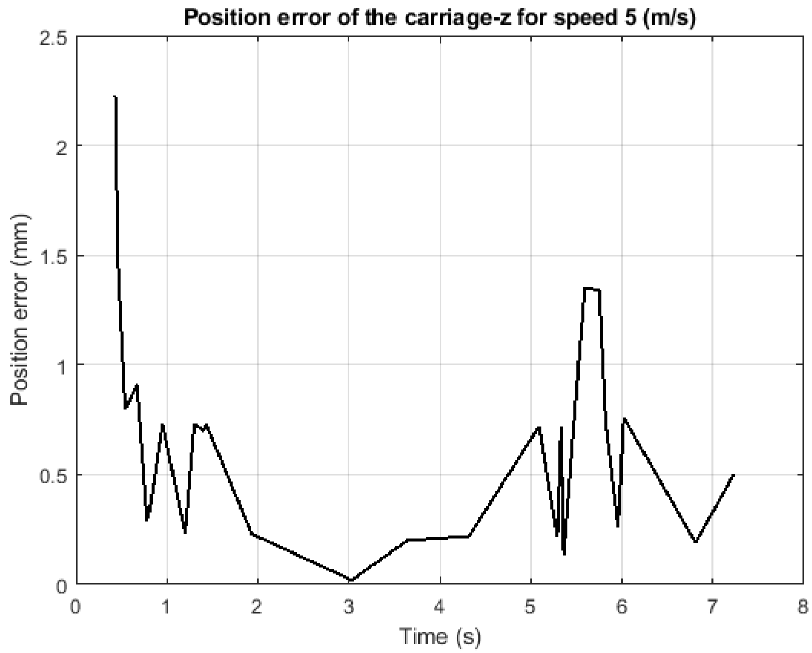

Figure 3.47. Position error of carriage-z in velocity 5 (m/s) with almost Max force 4×10^{4} (N)

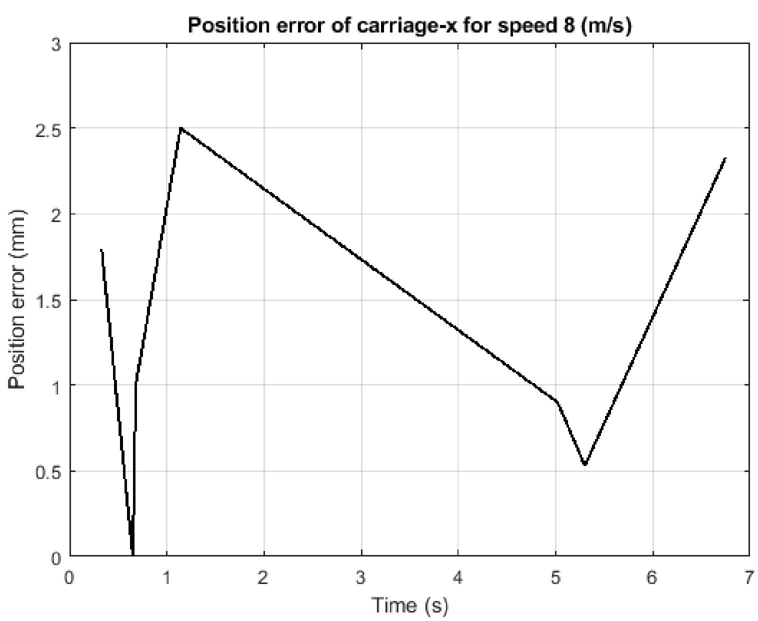

Figure 3.48. Position error of carriage-x in velocity 8 (m/s) with almost Max force $5,5\times10^{3}$ (N)

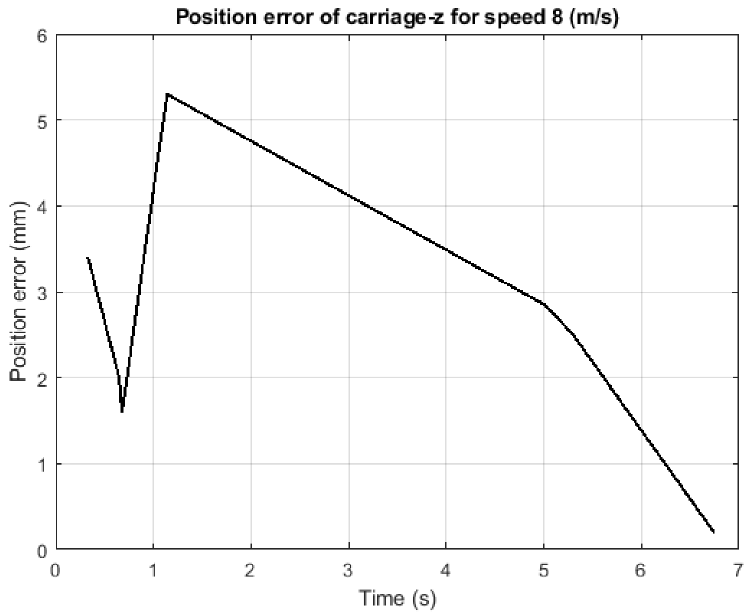

Figure 3.49. Position error of carriage-z in velocity 8 (m/s) with almost Max force 4×10^4 (N)

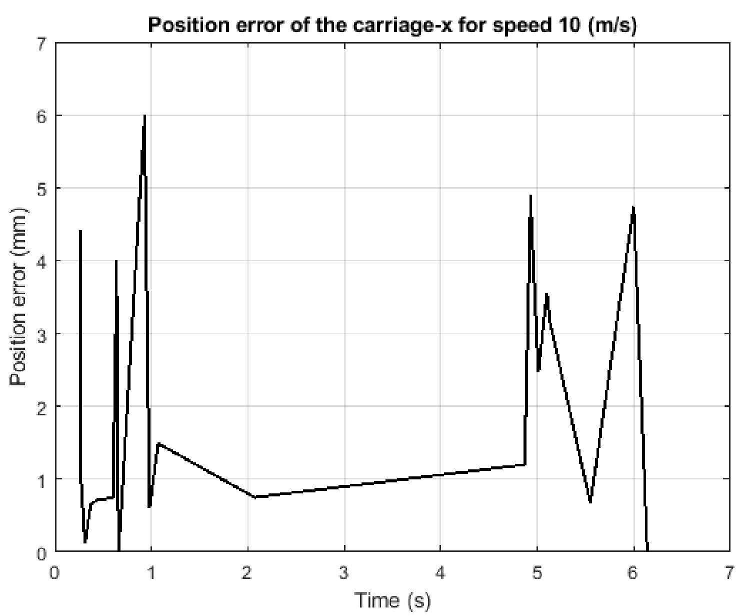

Figure 3.50. Position error of carriage-x in velocity 10 (m/s) with almost Max force 4×10^4 (N)

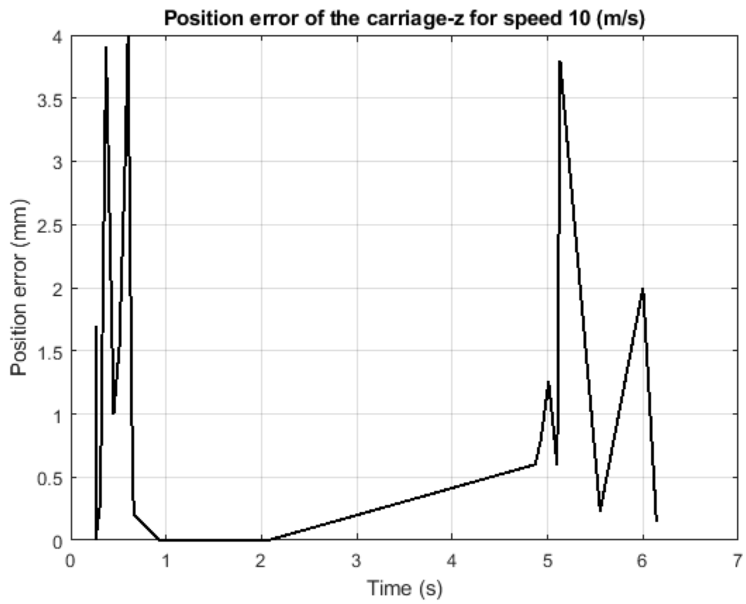

Figure 3.51. Position error of carriage-z in velocity 10 (m/s) with almost Max force 4×10^4 (N)

4 DISCUSSION AND CONCLUSION

In this thesis, the panel repairing line is simulated in Mevea. The Cartesian robot consists two part which each part can run in one direction. The linear motors should generate enough force to move with desired velocity. The advantage of using linear motor is that the speed can be high and no limitation in runing way. The main part of the project is to control the movement to do specific mission. Then the controller is combined with the model to make the real-time simulation.

4.1 Using the Digital Twin in developing the model

The survay is about using Digital Twin in real-time simulation of the developing panel repairing line which is used in the Raute Company to repair the defects on the produced plywood panels. Figure 4.1 depicts the steps of using Digital Twin in three phases of product life cycle (design phase, engineering phase and operation phase). the first step in developing this product is to create the graphic model of the product. This graphic model of frame and two parts of Cartesian robot are created in the Creo CAD software. Then the functional mock-up interface of the product is created in Mevea by assembling the part and define joints between them in order to have a virtual prototype of the real product. In addition the control system in Simulink and the initial data which are used in defining the model to use in computer simulation are other parts of the FMU. Afterwards, real-time simulation is started to analysis the position, velocity and applied force on the Cartesian robot in the whole working process. Hence the results are checked with the actual product then according to the requirement the actual product is modified to work in the real world. To develop the product it is needed to test the modified model in the real world again and collect the data of the position, velocity, acceleration by using measurement instruments or suitable sensors. After that, new information of the modified product transfer to the virtual model to use in simulation again. These steps are repeated to reach the optimized product. The main advantage of using the Digital Twin in developing the model by real-time simulation is that data can be updated in real-time by the user because data is transferred through the clouds that every user have access it. The user can be the person who is managing simulation, the company which is using the product and the costumers who are using the plywood from the product.

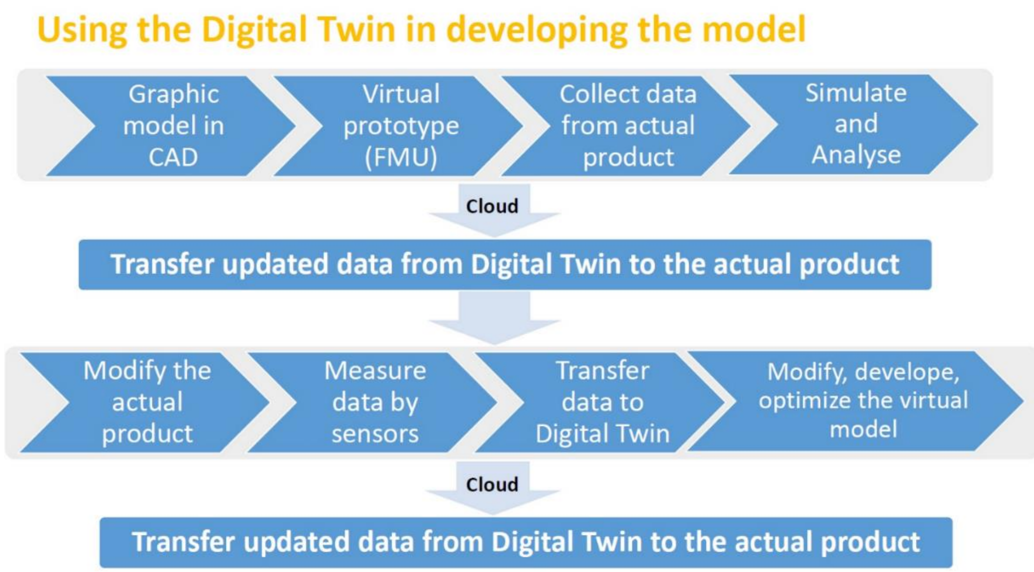

Figure 4.1. control system function based on velocity profile

As it mentioned in previous the control system algorithm is based on the generating force by defining the velocity profile that is formed on the desired position of the pathway of the defect on the plywood panel.

This method is useful, simple and fast for defining line shapes. (not undefined shape or complex curves). Because it is easy to define the function involves velocity profile. it is possible to define the velocity function related to the time or position. When the shape of the defect is simple like a line or line with slope it is desirable method. Since both parts are moving simultaneously, thus reach the goal positions with acceptable precision.

However, for complicated shape of defect the input function should be defined as the equation of the path and the velocity should be defined along with the pathway. In this case, the most important issue is that the two parts of the robots should reach the point in the same time, so define the velocity profile to create the required force to run to the defects. Thus the function is created based on the velocity relative to the time instead of the position. Furthermore, during the robot is doing the repairing task, the relative velocity between Cartesian robot and plywood panel is too slow. According to the shape of the defect the velocity of the each part of the robot is different. calculating the velocity of the each part respect to the pathway and permissible relative velocity is the other challenge in designing the controller.

4.2 Results

The linear motor which is used to move each part could produce enough power to move the part in high velocity depends on the weight of the part and friction between the part and the frame. The forces from the linear motors are modelled by the primitive force in Mevea so the force is generated in control system in Simulink based on the velocity profile. The main value of the force is provided by a propotional gain in PID controller. Therefore the amount of the force is related to the propotional gain and maximum demand velocity. If the maximum velocity and defined force is not enough to reach that velocity it is possible increase the proportional gain to boost the force to reach the demand velocity. Also increasing enough the force improve the velocity profile, but by improving velocity profile the accuracy to reach the desired points does not distinguish change. However small change (for example 0.1 m/s) on the velocity in constant proportional gain can change the force more and improve the accuracy of the positioning.

In this survey, the linear motor that is used in lengthwise part cannot generate enough power to reach the running velocity properly and change the velocity immediately. Thereby, different force powers are simulated and based on the results the another model of linear motor is suggested. Additionally, higher velocities for running phase are analyzed. By increasing the velocity the force should be increased to reach the demand velocity. Although using the higher force of moving the accuracy of reaching the target points is decreased.

According to the error plots which are demonstrated in chapter 3, when the velocity is higher than 5 (m/s) the position error is about 3 to 4 (mm) specially in the carriage-z this error is higher than in the carriage-x and this carriage needs to use a more stronger linear motor to move than the one which is moving in the crosswise direction.

In concluding, the linear motor which is moving the carriage-x, can run with desire velocity and achieve the target position with acceptable position error (1 mm). By increasing the velocity the position error is increased too. This linear motor satisfied higher velocity to 10 (m/s). However the average position error of the linear motor which is moving the carriage-z, is around 4 mm, by increasing the force, the error is reduced (by force 43749 N the position error is around 2 mm and in 62499 N the position error is around 1 mm). If the linear motor does not change, the maximum velocity, which is generated is 5.6 (m/s).

4.3 Future work

In this new model of panel repairing line with linear motor, the Cartesian robot can travel in all length of the frame so there is no limitation of movement. On the other hand, it is possible the Cartesian robots collide each other during running on the panel so need a sensor to recognize the present position and future position of each body.

The design controller to reach the position is the simple controller henceforth the controller can be improved for different complicated shape of the defect and for all the working robots on the line also the controller should prevent the collision between the robots.

4.4 Conclusion

In concluding, based on the results from the real-time simulation of the panel repairing line using linear motor instead of the Festo toothed belt provide higher running velocity with reaching the target positions with acceptable precision. The point is in selecting the suitable linear motor based on the power to generate enough force to move the part by desirable velocity in the short time. Therefore, it is important to generate enough force to follow the proper velocity profile. Hence, as reported by using Digital Twin in simulating the panel repairing line, the linear motor type 1FN3600-4WD30-0BA1 which is used for the carriage-z dose not generate enough power to have allowable accuracy.

5 SUMMARY

In this survey, the Digital Twin is used to real-time simulation of panel repairing line. The panel repairing line consists one frame and four Cartesian robots which are running and working through the frame to repair the defects on the plywood panels. Cartesian robots are working in two directions – crosswise and lengthwise – but each robot includes two parts that each part is moving in one direction. Hence, the system consists two degrees of freedom. The aim of this thesis is to find the accuracy of reaching the target points on the plywood panels when linear motor is used to run through the panel repairing line. In addition, is it possible to increase the running velocity, then do not lose the position accuracy?

In following the mission plan of the panel repairing line is expressed: first the plywood panel is fed to the line, then the camera on the beginning of the line recognizes the defects on the plywood panel. Plywood panels travel the line with constant velocity. The location of the defect is transferred to the robots in order to mend the faults then repairing tasks are divided between robots. Henceforward the first robot runs to the beginning of the defect by speed 5 m/s. This running velocity is constant for both parts of the robots to move from one point to another point. After reaching the defect, the velocity should be reduced to the working velocity. The relative working velocity respect to the panel is 0,25 m/s. Thus the working speed of each part of the Cartesian robot depends on the shape of the defect. The robot does not stop through the line and always go from one defect to another defect also can go forward and backward on the line.

In this project, the graphic model of each part is created in Creo then converts to the Mevea to make a virtual prototype of the system. All parts are assembled in Mevea. Two different linear motors are used to move each part of the Cartesian robot. The created force by linear motor is modeled as a primitive force. Then the control system is designed in Simulink to control the movement of the Cartesian robots.

According to the results of the simulation, the position error is around 2 mm and in most points is 1 (mm) that is acceptable. By increasing the velocity, the precision is reduced and needs more power to provide sufficient force to have an allowable accuracy to achieve the purpose points.

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