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A Model-Based Mechatronic System Design and Integration Process

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Abstract

In contemporary mechatronic product development, embracing an interdisciplinary approach has become imperative to manage potential integration risks. This research paper introduces a viable solution that combines Automation Studio and the VDI 2206 methodology to design mechatronic systems. The study's findings highlight the efficacy of this interdisciplinary approach in effectively addressing early challenges associated with multi-domain integration. It enables simultaneous evaluation and resolution of limitations inherent in traditional design methods. Successfully applied to develop an automated garment folding machine with a PLC controller, the proposed process proves to be a valuable tool in optimizing mechatronic system development. The system, designed using this process, relies on a real-time computational model as its foundation, laying the groundwork for constructing a digital twin in the future. This ensures a comprehensive representation of the system, facilitating enhanced understanding and performance assessment during the development and operational phases. The adoption of such an approach signifies a significant step forward in advancing mechatronic engineering and ensuring the successful realization of complex and efficient systems.

Keywords: VDI 2206, interdisciplinary engineering, mechatronics, PLC, automation studio.

1. Introduction

The significant progress in information technology and the simultaneous integration of various fundamental engineering disciplines have led to the development of mechatronics systems. A mechatronic system requires a multidisciplinary engineering approach to design, develop, and validate. Most of the products today are considered mechatronics systems because they contain at least two of those systems (mechanical components, electronic systems, intelligent control systems, and information technology). One of the critical challenges in developing modern mechatronic systems is the tight integration of various technical fields from the first stage of the design phase [1]. This aims to help engineers avoid any error when integrating two or more system domains from the early stage and reduce costs in later processes. Model V (Fig. 1) in VDI 2206 [2] - the methodology introduced for the mechatronic systems design process, is proposed to meet the continuous integration challenges in product development to shorten the time, improve quality and reduce costs. The V-model and additional customizations are extensively researched and proven to be effective [3, 4]. V-model have been used to develop various kind of system, such as an automotic system [5], an optomechatronic system [6], Hydrogen Production and the Automatic Filling Control system [7], Defect Detection System on Stamping Machine [8] that using the image processing method and a photovoltaic charging station (PVCS) [9] Additionally, Jens Bathelt and colleagues introduced the education-oriented mechatronic design guideline based on VDI 2206 (which stand for Verein Deutscher Ingenieure 2206). This guideline focuses on mechatronic systems controlled by a PLC (Programmable Logic Controller) and aims to provide a framework for designing such systems in an education-oriented manner [10].

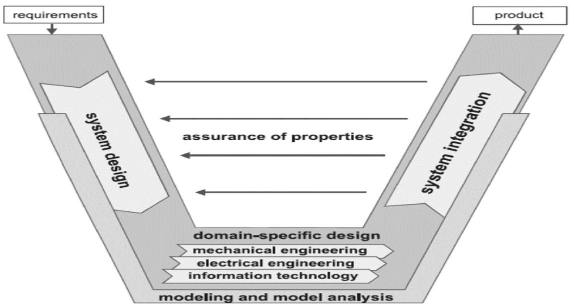

Fig. 1. V-model

This study applies the VDI 2206, and the process proposed in [10] to suggest a methodology of designing and validating mechatronic systems with PLC controllers. This method involves utilizing the Automation Studio tool to integrate all three aspects of mechatronic systems (mechanical, control engineering, and electro-pneumatic engineering) right from the outset of the design process in order to

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address the challenge of interdisciplinary data linkage. This approach will be exemplified through the experimental design of a folding machine system. By doing so, this solution aids in the concept design process and resolves integrated problems from the beginning of system design. Its primary objective is to demonstrate the feasibility of the concept in both mechanical and control systems, as well as to validate the general operational principles and key design requirements.

2. The Integrated Design Process in Mechatronics to Simulate and Evaluate the Dynamics and Control System

2.1. Determining the Objectives and Requirements of the Mechatronic System to be Designed

Gathering information about the product is crucial and includes details such as application, operating conditions, environmental factors, and pricing. Analyzing market research, customer needs, preferences, system requirements, and aesthetics help determine preliminary design specifications. The process involves identifying and analyzing target market users and their preferences, defining system requirements, determining functional parameters, and drawing a conclusion to answer key questions about the design system [10].

2.2. Conceptual Design, Defining the General Functional Parameters and the General Structure of the System.

Concept design is the first stage of designing a mechatronics system, where interdisciplinary ideas are proposed to solve a design problem. It heavily relies on user and system requirements and shapes the overall vision. Similar to [10], the following steps include:

1. Identifying, verbally describing, and analyzing the required system:

a) Understanding the nature and purpose of the system,

b) Identifying the overall tasks, functions, and sub-functions the system needs to perform,

c) Defining the desired behavior and tasks expected from the system,

d) Determining the physical appearance and overall dimensions of the system,

2. Establishing the preliminary system architecture and subsystem structures, including mechanical, electrical, and control components,

3. Dividing the system into subfunctions, subsystems or components with distinct functions by identifying the main subsystems and special components, defining their associated functions, and analyzing their interactions and interdependencies;

4. Creating a system structure, hierarchy, and describe the flow of information/energy/materials between component,

5. Specifying mechanical properties like material, size, volume, DOF, and coupling type. Developing a basic model for controller design, control software, and CAD; Optimizing controller performance by deciding on mechanical properties,

6. Conducting morphological analysis to propose potential solutions for each function in the functional structure model. The best solution is evaluated based on requirements and feasibility which helps develop an initial understanding of the required sensors, actuators, and interfaces,

7. Constructing a preliminary system block diagram illustrating the main components of the system,

8. Conducting a preliminary feasibility study, including cost and benefit analysis.

2.3. Implementing Single-domain Design, Combining Modeling, Analysis Simulation, and Single-Domain Evaluation, and Integrating Sub-Domains with Automation Studio Tools

In this stage, we modified the process mentioned in [10] to make it more suitable for the system using PLC and applied the Automation Studio tool. The reason for doing analysis, evaluation, integration, and optimization at the same time is to make sure that every part of the system gets checked and improved together while it's being designed.

2.3.1. Mechanical domain.

The Automation Studio tool is used for preliminary mechanical system design, including determining construction requirements, dimensions, materials, and joint combinations. The tool models separate subdomains such as pneumatic and hydraulic components, along with 2D mechanical modeling using the Mechanism tool. The software facilitates accurate design simulations, equipment selection, and cost calculations by offering hydraulic and pneumatic models, brand catalogs, and testing of proposed sensors and control devices during the design process.

2.3.2. Electrical-control system design.

The control panel was designed using Automation Studio's modeled elements such as buttons and switches. A Grafcet diagram was used to determine the system's control principle based on initial preliminary design results. The PLC was chosen as the main control component, followed by proposing sensors, control devices, and actuators. The SFC control program was created using Automation Studio tools to control the system based on the Grafcet diagram.

2.4. Integrating, Analyzing and Evaluating Multi-Domain Systems with Automation Studio Tool

2.4.1. Mechanical-pneumatic integrating and system dynamic analysis performance.

Automation Studio has limited capabilities when it comes to modeling mechanical structures due to its simplistic elements, which require users to simplify their models. However, the Mechanism tool's strength lies in its integration with pneumatic components, allowing for dynamic calculations and testing of how these components work with other mechanical structures under certain pneumatic controls.

2.4.2. Integrating the control system and human-machine interface, mechanical construction and testing of system operating principles, and analyzing system operability.

Automation Studio simplifies system integration by linking variables among pneumatic components, control circuit components, and control panel components. The software also allows the programming of SFC based on basic schematic diagrams and testing of the entire integrated system for correctness. Productivity analysis is performed through simulations of various parameters such as operating pressure and throttle valve value to increase productivity.

3. Case Study

3.1. Determining the Objectives and Requirements of the Mechatronic System to be Designed.

While acknowledging the limitations of this research, the research team establishes certain system requirements instead of conducting investigations into user preferences or market demands. The proposed system must be capable of folding shirts in sizes ranging from women's size M to men's size XXXL (shirt sizes 580 x 420 mm to 785 x 580 mm), with a productivity rate of 20 seconds per shirt. The system must prioritize electrical safety measures for both the operator and the system itself.

3.2. Conceptual Design, Defining the General Functional Parameters and the General Structure of the System.

Conceptual design involves defining system parameters and structure, identifying components like actuators and interfaces, analyzing requirements, subdividing functions, assessing morphological aspects and estimating the dimensions of important parts.

1. Defining the system, conducting verbal descriptions and analyzing system requirements:

a) The system can fold clothes from sizes 580 x 420 mm to 785 x 580 mm.

b) The main function of the system is to perform semi-automatic garment folding through control from buttons. Perform 2 modes: Mode 1 folds an entire shirt, and Mode 2: folds each step depending on the operator.

c) Carry out the folding of the shirt according to the steps of the folding process as shown in Fig. 2.

d) The system will take the form of a table with the selected size (Fig. 3) larger than the shirt size placed on 4 folding sheets for the purpose of folding clothes.

2. Determining the preliminary system architecture, subsystem structures: the actuator performs system tasks, the part of the human-machine interface device generates the signals that control the system operation in different modes, electrical-control part.

3. Dividing the function, the overall system into subsystem functions or even components where the operating principles are special.

a) The mechanical part consists of 3 basic parts: plates for folding clothes, a rotational mechanism for plates and a table to attach the above mechanisms and suitable for the operator.

b) The user interface section collects control commands.

c) Control electrical part: provide power to the system, and transmit control signals automatically

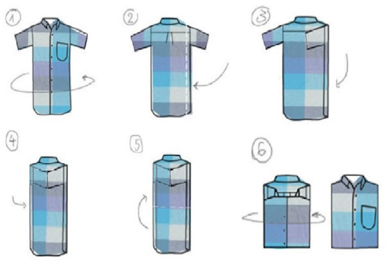


Fig. 2. Steps to fold clothes in practice

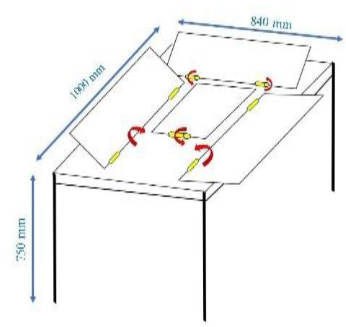


Fig. 3. Preliminary shape and the initial dimensions of the design

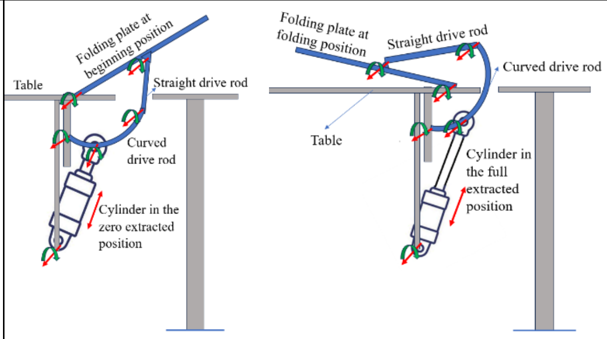
4. Morphological analysis: Construct a table of morphology and analyze correspondingly (Table 1).

According to the specifications outlined in Table 1, Solution 1 has been chosen for the design of the cloth folding system. Following this approach, it is determined that 8 position sensors are necessary to accurately ascertain the positions of 4 cylinders (each cylinder for a folding plate) and 4 control valves associated with the cylinder valves.

5. Analyzing the system's functional structure, hierarchy, and the flow of information, energy, or materials between its components. (Fig. 4)

6. Estimating overall dimensions of mechanical parts.

Table 1. Table of functions, subcomponents and corresponding solutions

Sub-function	Solution 1	Solution 2
Structural mechanics of folding plate	 - Using metal grids to minimize mass and hence requires less lifting force, lowering production costs	 - Using special metals as a folding mechanism - This will result in unnecessary waste and a requirement for higher force to make it move
Mechanism for folding plates	 -Utilizing 4 cylinders as the actuators of the folding mechanism. The detail of our mechanism is described in the picture above.	- Providing power to the folding panels by installing motors on each panel. - This solution is inefficient because the torque produced by the small-sized motor is usually insufficient. The design to mount the motors is difficult. In the case the folded sheet structure has not been mesh-refined, raising the plate will be challenging.
The system control panel	- Using buttons and signal lights for each function - Reduce design costs	- Using the HMI display to control system functions - High-cost
Control device	- Using PLC +) Faster scan time, capable of computer communication and monitoring +) Flexibility in setting control algorithm, easy to troubleshoot or change	Using the digital controller +) System stability and signal error during continuous data-to-digital conversion +) Complexity of algorithms causes software errors when controlling

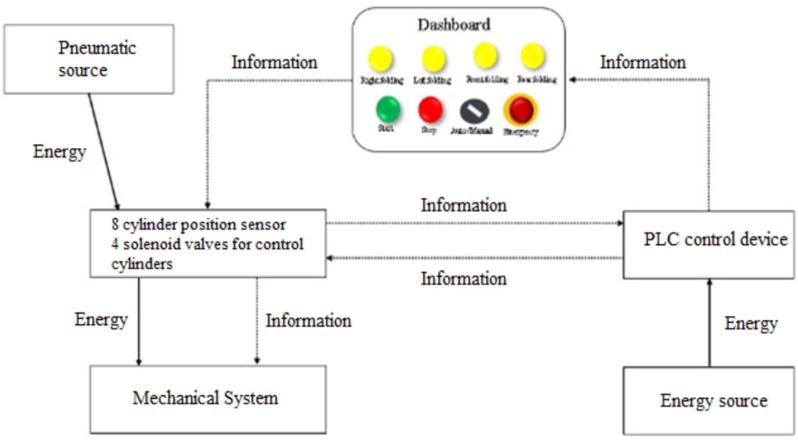


Fig. 4. System energy, information and data flow.

Based on the shirts size, which are 580 x 420 mm to 785 x 580 mm, the table size and the system mechanism in solution 1, the dimensions and mass of mechanical parts are estimated as shown in Table 2. The Festo DSNU cylinder, which follows ISO 6432, with a stroke of 200 mm is chosen. After calculating the total mass, we see that the total weight of the cylinder that needs to be lifted is approximately 1.23 kg. Based on the maximum load of cylinders, there are the following cylinder options with a 200 mm stroke as shown in table 3.

In the following section, a dynamics model and simulation will be performed in Automation Studio based on the parameters of 2 given cylinders (Table 3). After that, the right cylinder will be selected.

Table 2. The estimated sizes and material parameters of the system's mechanical components.

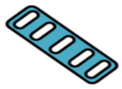
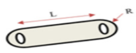
Part	Estimated shape	Estimated size	Estimated material	Estimated volume
Upper folding plate		Acreage: 170x285(mm^2) Thickness: 4 mm	Plastic	200g
Lower folding plate		Acreage: 720x210(mm^2) Thickness: 4 mm	Plastic	600g
2 Side Folding Plates		Acreage: 700x260(mm^2) Thickness: 4 mm	Plastic	800g
Straight drive rod		Thickness: 4 mm R = 10mm; L = 130mm	Aluminum alloy	210g
Curved drive rod		Thickness: 3 mm	Aluminum alloy	220g
Cylinder	~	Stroke: 200 mm	~	~

Table 3. Parameters of selected cylinders for cylinder selection

Cylinder diameter	12 mm	16 mm
Piston radius	6 mm	6 mm
Spacing of two rotary joints (included accessories)	305 mm	315 mm
Cylinder mass	155 g	181.9g
Piston mass	58.5 g	63 g
Cylinder axial centre of gravity	126 mm (From the rotary joint attached to the cylinder)	130 mm
In the axial centre of the piston	154 mm (From the rod end)	162 mm
Moment of inertia parallel to the axis of rotation at the centre of gravity of the cylinder	1,9.10-3 $kg.m^2$	2,9.10-3 $kg.m^2$
Moment of inertia parallel to the axis of rotation at the piston's centre of gravity	3,3.10-4 $kg.m^2$	4,3.10-4 $kg.m^2$

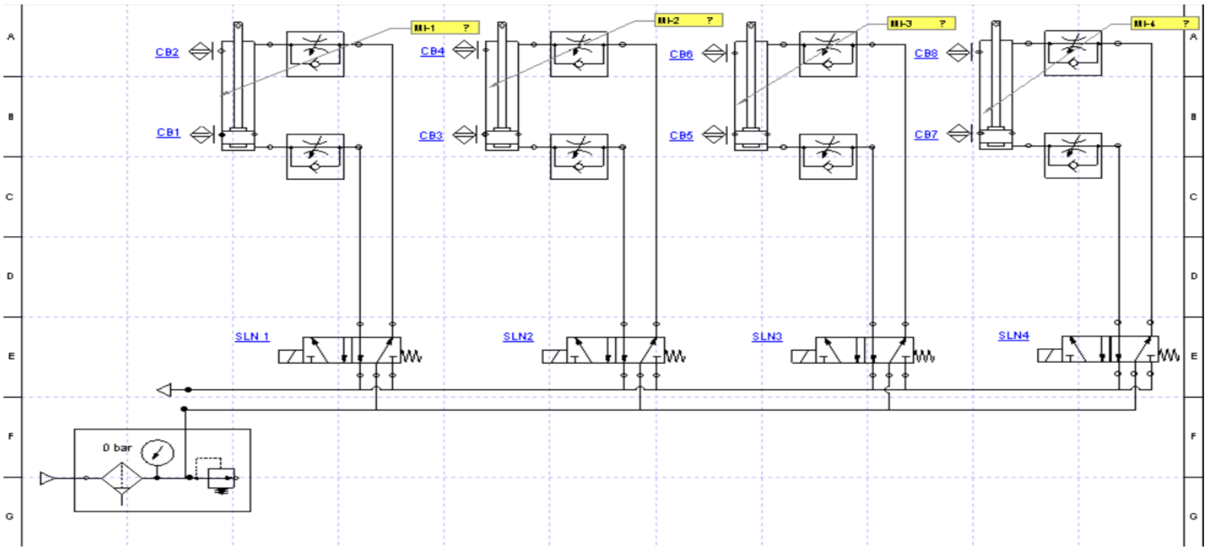


Fig. 5. Pneumatic circuit built in Automation Studio

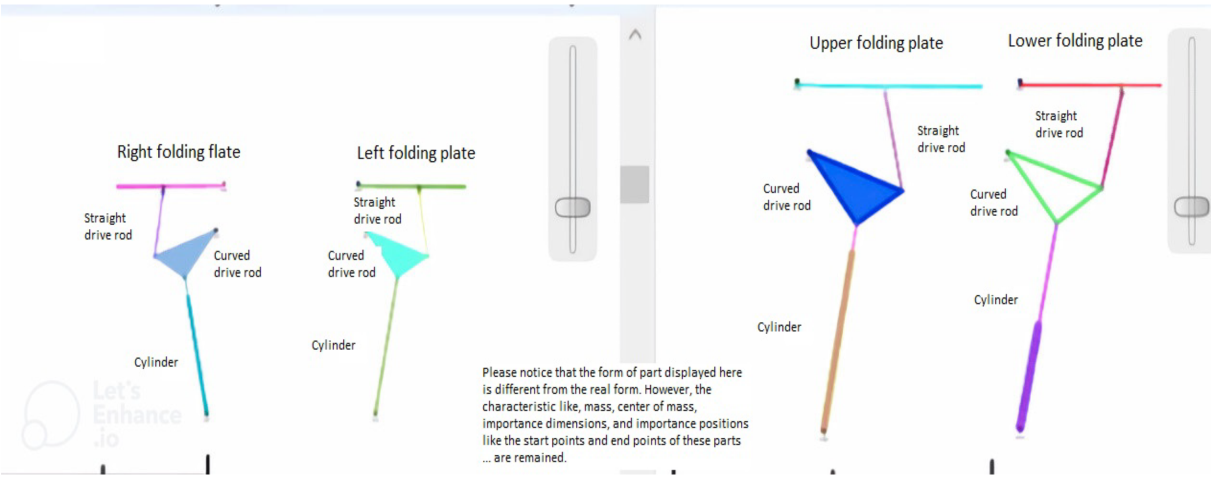


Fig. 6. 2D mechanical diagram built in Automation Studio.

3.3. Deploying Single-Domain Design, Combining Modelling, Analyzing Simulation and Single-Domain Evaluation, Integrating Subdomains with the Automation Studio Tool

3.3.1. Mechanical domain:

The pneumatic cylinder system for the pressurized folding machine is designed and simulated (Fig. 6) with the elements modeled ideally (ignoring energy loss or leakage). The pneumatic system consists of 4 cylinders, 4 control valves to control the cylinder, 8 throttle valves, and a pressure regulator to regulate its operating pressure. The pipes and max value of the throttle diameters are set to 4mm.

From the estimated dimensions for the 3 selected cylinders, the values of centroids of objects in 2D such as the center of gravity position, and the moment of inertia are calculated. From 4 mechanical models in the Automation Studio are built through joint elements, embedded bodies and cylinders (Fig. 7).

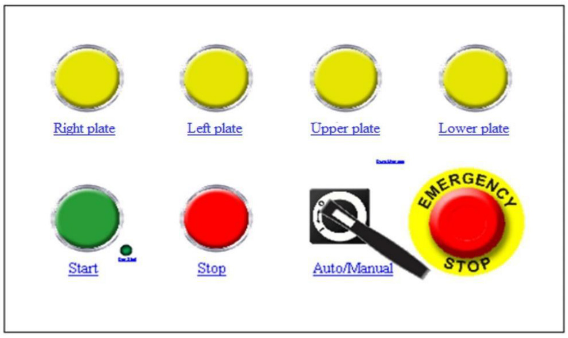


Fig. 7. System Control Panel

3.3.2. Electrical-control system design.

Based on operational requirements, we have constructed a control panel (refer to Fig. 8), utilizing buttons to generate control signals. The Grafcet schematic diagram (Fig. 9) has been developed considering control signals, system requirements, and the pneumatic system. The PLC serves as the central control element, with pre-designed control panels, solenoids acting as control elements for cylinders, and sensors determining cylinder positions. The research team has determined the signal flow of components, created the system's inputs and outputs, and constructed the circuit within Automation Studio (Fig. 10). An SFC program has been developed using tools within Automation Studio (Fig. 11) to control the system based on the principles outlined in Fig. 8.

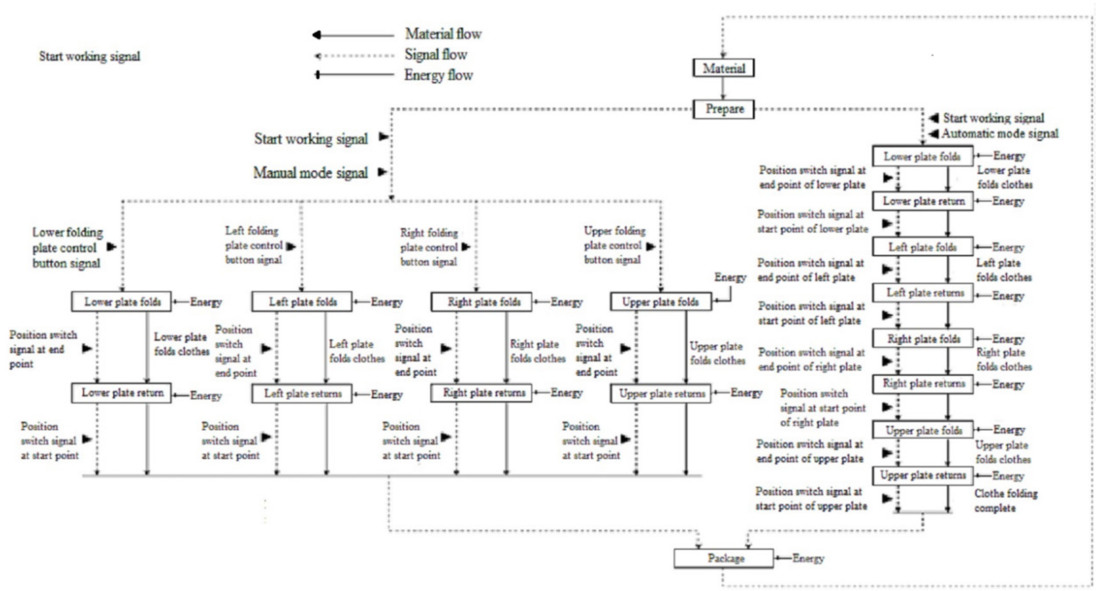


Fig. 8. Diagram of the principle of operation in the form of grafcet

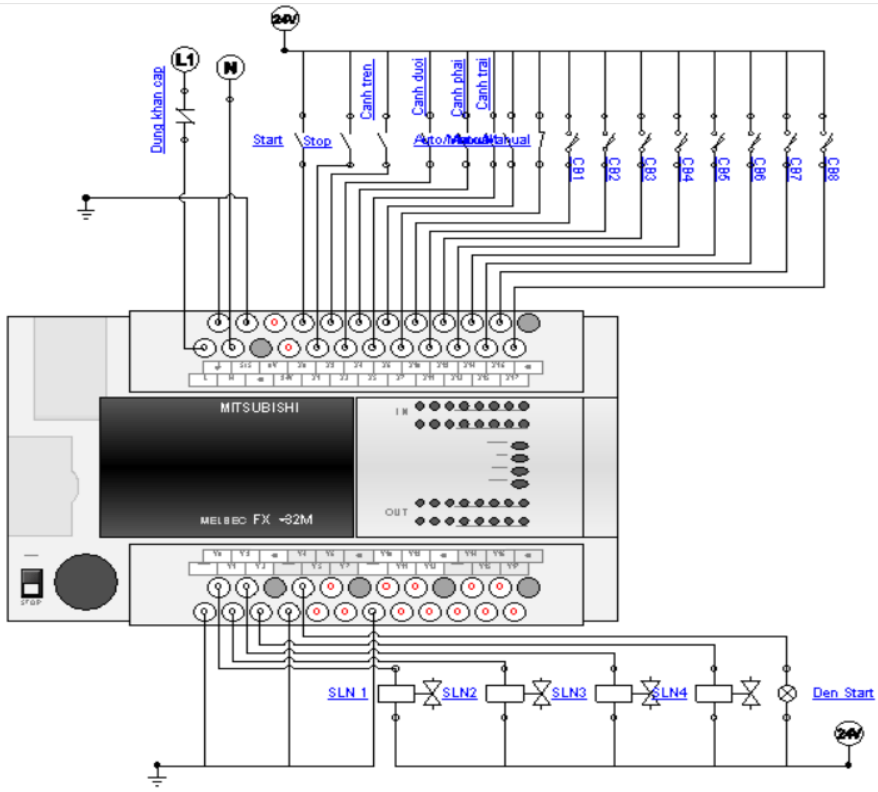


Fig. 9. Circuit-control design in Automation Studio

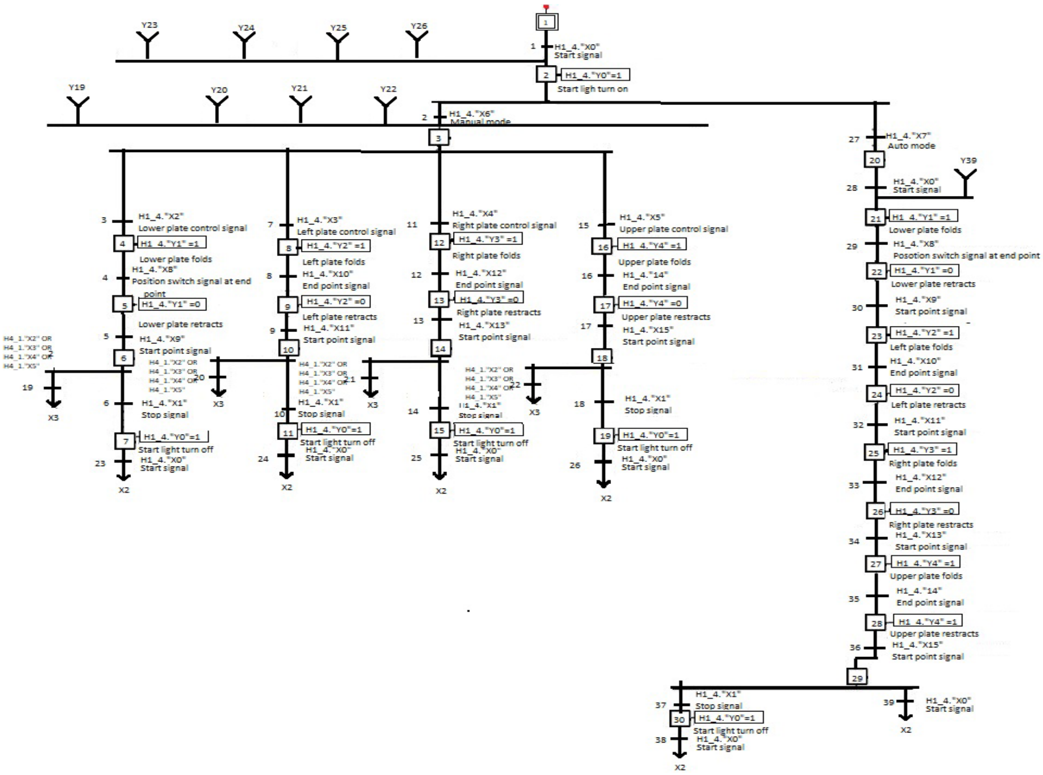


Fig. 10 SFC program for system

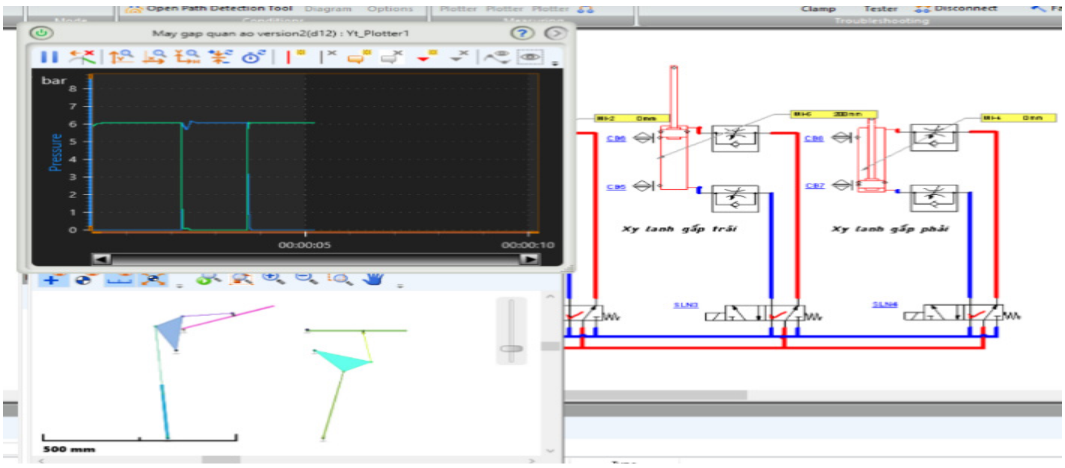


Fig. 11. The pneumatic-mechanical integration simulation with a system using 12mm diameter cylinders.

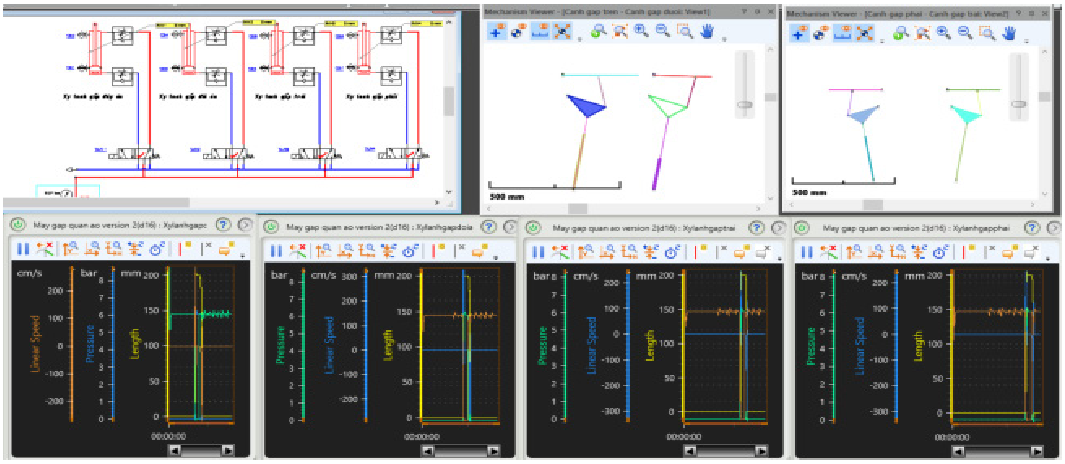


Fig. 12. Pneumatic-mechanical integration test with the system using 16mm diameter cylinders.

3.4. Integrating, Analyzing and Evaluating Multi-Domain Systems with Automation Studio Tool

3.4.1. Mechanical-pneumatic integration and system dynamic analysis.

The Mechanism tool integrates mechanical and pneumatic components. The Automation Studio enables system dynamics analysis using simulations, which showed that a 12mm piston diameter cylinder is insufficient to retract the folding arm, (Fig. 11) but a 16mm radius cylinder works well (Fig. 12). The software calculates position, speed, and pressure values for both chambers of the cylinder over time, which are shown in Fig. 12. Fig. 12 shows the values of position, speed, and pressure of 2 chambers of the cylinder over time.

3.4.2. Integrating Control System and Human-Machine Interface, Mechanical Construction and Testing of System Operating Principles, Analyzing System Operability.

The system operates by integrating the variables of its constituent elements. Through simulation (refer to Fig. 13), the entire system is comprehensively evaluated, enabling assessment of the single-domain design's correctness within the context of the overall system. This approach facilitates the evaluation of various system-wide parameters, including productivity and the intuitive assessment of the PLC program. The throttle valve diameter can be adjusted to enhance speed and meet performance requirements. Its maximum setting is dictated by the cylinder type, which, in this study, has a 4mm diameter. If it is not possible to change the piston diameter, the operating pressure can be increased. When the throttle valve value is set to 0.2, the time from pressing the start button to when the last cylinder returns to 0 mm is 12.9 seconds. This result changes to 7.3 seconds when the value is set to 0.5 mm, and to 6.9 seconds when set to 1 mm. These results are calculated from the table of values over time from the graph Fig. 14.

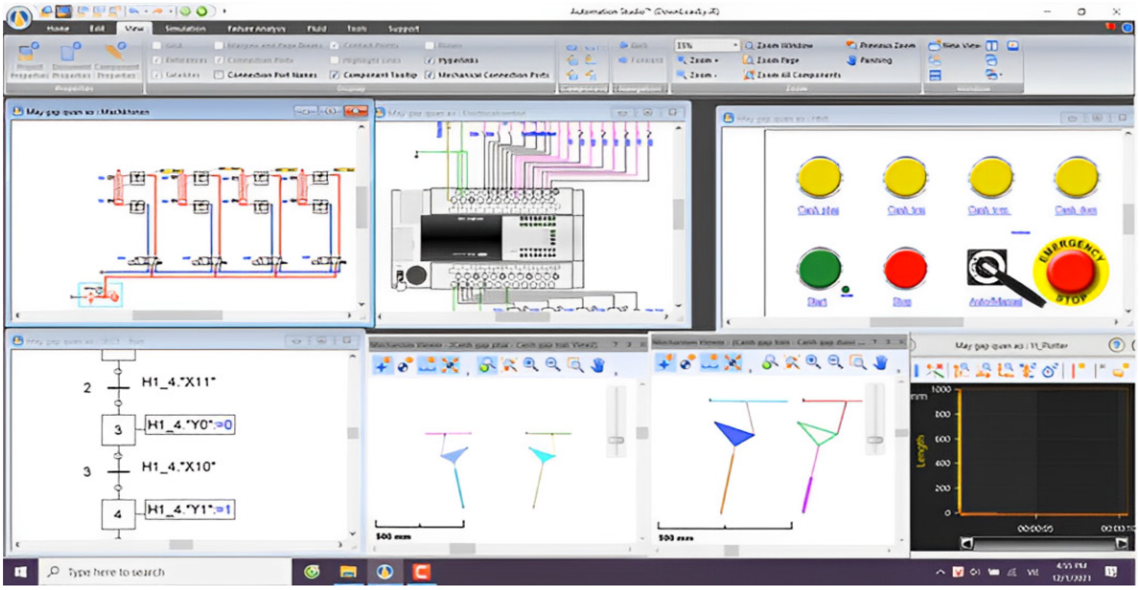
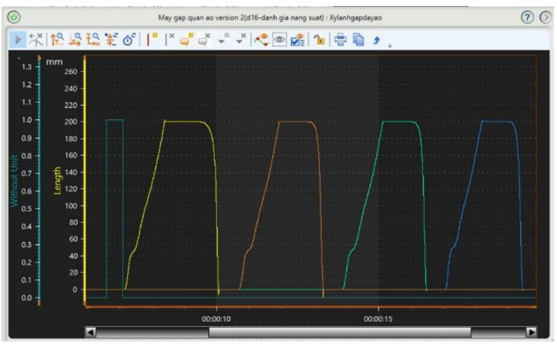
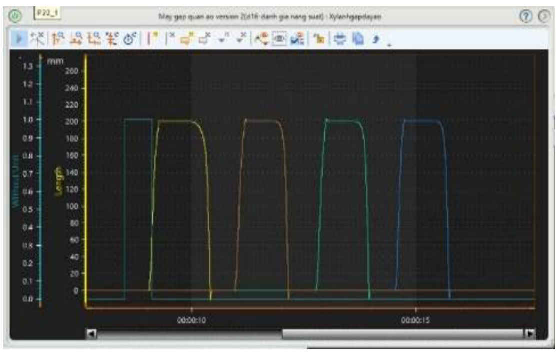


Fig. 13. Integrated multi-domain mechanical-pneumatic, electrical control, control panel, and control program system.



a) The signal value of the Start button and the position of 4 cylinders over time when d_{min}/d_{max}= 0.2/4 mm.



b) The signal value of the Start button and the position of 4 cylinders over time when d_{min}/d_{max}= 0.5/4 mm

Lower plate — Right plate
Left plate — Upper plate

Fig. 14. The start signals and cylinders' position of a Clothing Folding Machine in a working cycle.

The utilization of Automation Studio has facilitated the estimation of pressure values in accordance with the operational process of the system, while ensuring adjustments are made as the system operates in compliance with the correct control logic. Additionally, it aids in the validation of the operational principles of the visualization system without the need to analyze intricate code. Furthermore, it assists in accurate estimation of the system's operating time based on the principles of system control. When compared to simulating the control and pneumatic mechanical systems separately, sequentially (which is called sequential design method) it is hard to estimate the cycle time without seeing how all system works. Besides, limited interdisciplinary communication can lead to suboptimal integration and potential conflicts in the system idea, as each discipline may develop its components without considering the broader system implications. Without concurrent input from all relevant disciplines, the final design may not fully leverage the potential synergies between mechanical, electrical, and control engineering, leading to a suboptimal solution. Sequential design method ultimately results in a longer time to market and increased costs, as iterative changes and rework in the later stages consume additional resources.

4. Conclusion

The process of designing and integrating the mechatronic system using the Automation Studio tool was presented and implemented through the design process of a PLC-controlled garment folding machine system. That is an immensely powerful tool that encompasses a wide range of functions and elements to simulate various system components, including mechanical, hydraulic, pneumatic, and electrical controls. It serves as an exceptional aid for designing, simulating, and evaluating single-domain systems, as well as facilitating integration and multi-domain assessments of mechanical, electrical, and control principles to assess system performance right from the initial stages of product design and development. The software's capabilities in kinematic-control design and dynamic analysis, coupled with its user-friendly interface for easily modifying element characteristics, enable swift and efficient system evaluations. When evaluating mechanical structures that primarily depend on sliding, rotating, and fixed joints, along with parameters such as the center of gravity mass and moment of inertia, it is beneficial for validating the dynamic system which also contain cylinders based on simple dynamic model.

By utilizing Automation Studio, we can validate system concepts and ensure accurate designs right from the outset, enabling real-time updates across all system components when changes occur in any primary area, such as mechanical or control engineering. This seamless coordination between subdomains ensures smooth cross-system functionality. Additionally, the use of animation tools allows for the creation of comprehensive system design and manufacturing documents from the conceptual stage, facilitating easy tracking and traceability. These foundational data also serve as the building blocks for constructing a digital twin, which enables ongoing system monitoring post-completion. Once the conceptual design is confirmed, the subsequent phase involves the detailed design of subdomain systems. This entails constructing dynamic models, 3D representations, and meticulous electrical diagrams, among other aspects. Following the V-model, the integration of all systems allows for the identification and resolution of any interdisciplinary issues, ensuring a comprehensive and robust final design.

In conclusion, the integration of system elements through the association of their variables enables the simulation and evaluation of the entire system. This approach allows for the assessment of the correctness of individual domain designs in the context of the larger system. Additionally, it facilitates the evaluation of productivity and the performance of the PLC program in an intuitive way. Such simulation tools can be valuable in optimizing system performance and identifying potential issues early on.

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