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Bipedal walking robot platform with a vertically stabilized base usable as a bipedchair for disabled people

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Keywords: walking robot, biped locomotion, actuator, centre of gravity.

Abstract: The article deals with the design of a concept for a mobile robotic platform for transporting equipment or people. For disabled people, this system can represent an alternative to a wheelchair with better mobility in an urbanized environment. The proposed solution is unique in that it maintains a stabilized vertical position of the base.

1 Introduction

A large number of people have a medical handicap and cannot walk with their own feet. These are different diagnoses that do not have a favourable prognosis for improving the ability to walk in normal conditions. There are also cases where it is a permanent loss of mobility with the help of the lower limbs. For these cases, it would be appropriate to design a suitable device that would replace walking with the legs. Standard wheelchairs are a solution that often has a problem with obstacles that occur in urbanized environments, so there is room for walking structures. However, commonly used kinematic walking structures create a side-to-side rocking motion to maintain static and dynamic stability while walking. The application of this conventional way of walking would mean uncomfortable walking for a person. It would therefore be a biped chair that could handle obstacles such as stairs and curbs and other unevenness in the exterior.

The goal is to design a kinematic structure with as few degrees of freedom as possible and at the same time a good ability of mobility with minimal swaying movements to the sides. A small number of degrees of freedom also means a small number of actuators, and thus the energy requirements and range of the created structure also decrease. Walking structures have a disadvantage in terms of energy balance compared to wheeled structures, so suitable kinematic structures with a lower number of degrees of freedom could be a better solution. [1-29].

2 Robotic platform concept design

The first concept (Figure 1) contains three degrees of freedom in each leg and uses three rotary actuators in both legs. This simplified model represents the simplest structure that is similar to human kinematics.

One actuator would have to be located in the hip joint. The second actuator would have to be located in the knee joint and the third actuator could be in the ankle joint. The movement could be realized by crossing each other's feet (Figure 2).

However, the use of this kinematics entails a rocking motion with a large change in the position of the base of the robot in the vertical direction. If we consider that a person who is being transported would be placed in this base, then this movement is very uncomfortable.

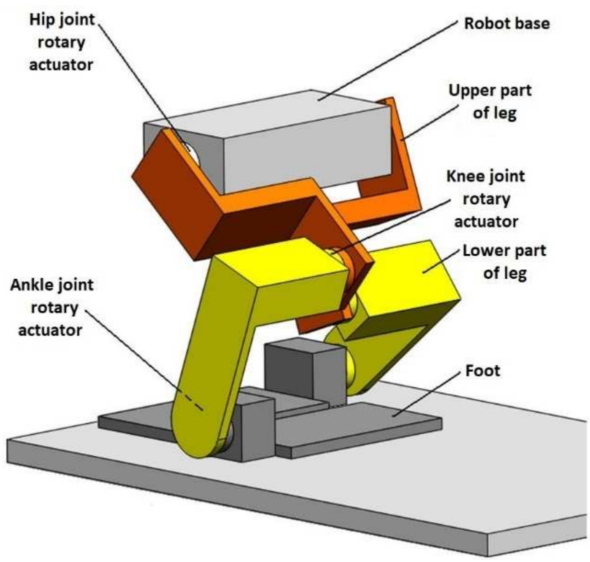

Figure 1 Biped robotic platform concept A

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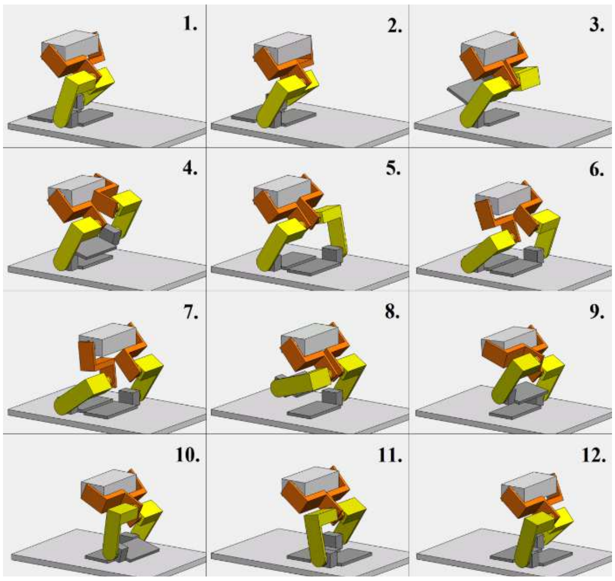

Figure 2 Walking algorithm of biped robotic platform concept A

Another robotic platform concept (Figure 3) no longer takes inspiration from human kinematics, but also includes a linear actuator and two rotary actuators in each leg. The linear actuator replaced the rotary actuator in the knee and thus created the possibility of lifting the leg while crossing the other leg without vertical displacement of the robot base (Figure 4). In terms of energy, however, this concept is still demanding, and the effort is to reduce the number of actuators even more.

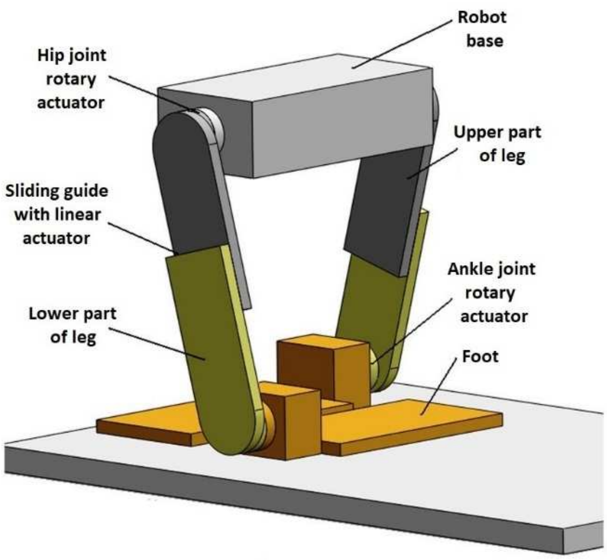

Figure 3 Biped robotic platform concept B

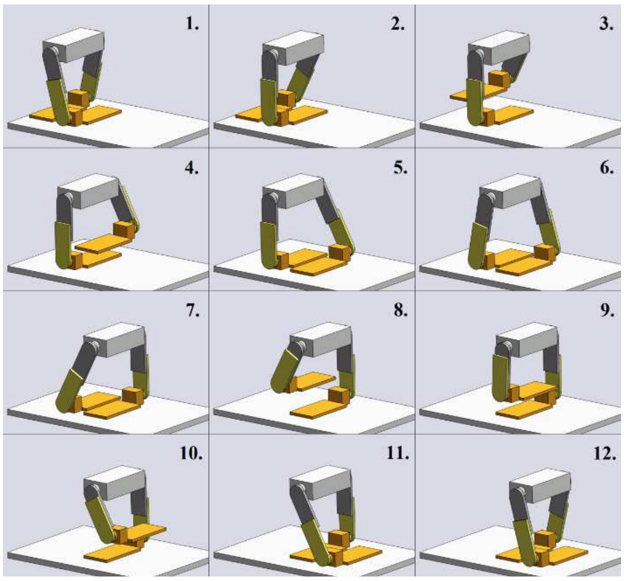

Figure 4 Walking algorithm of biped robotic platform concept B

Another concept is a design with two actuators in each leg (Figure 5), while the rotation is performed in the ankle joint and the linear movement of the actuator is performed in the hip joint, where this linear actuator is used to realize just the crossing of the legs and the compensation of the vertical movement activity so that the robotic base did not change its vertical position (Figure 6). This concept provides with two actuators the possibility of walking, even while maintaining the vertical position of the base.

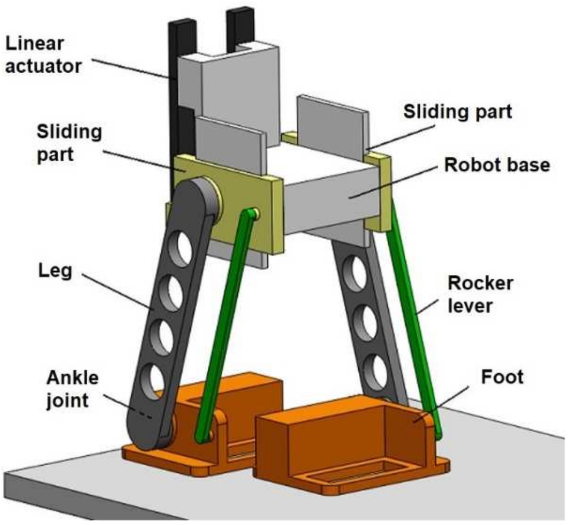

Figure 5 Biped robotic platform concept C

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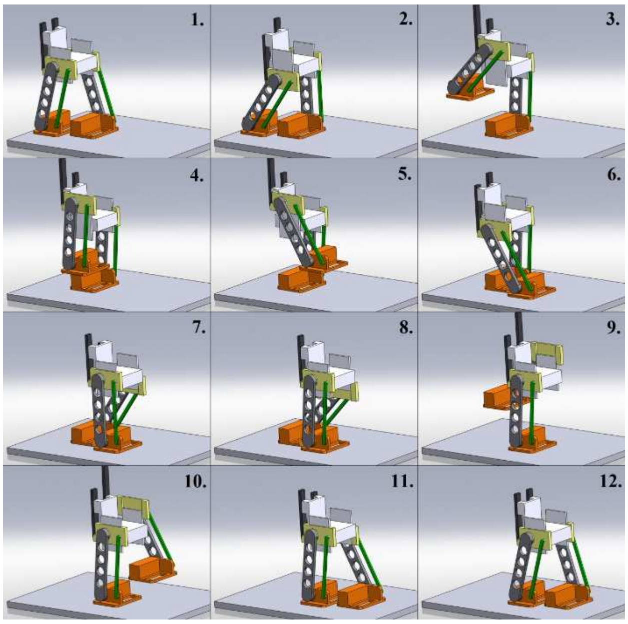

Figure 6 Walking algorithm of biped robotic platform concept C

The concept (Figure 5) in this form is only applicable for walking in one direction. In order to be able to change the direction of walking, a rotating mat with another rotary actuator is proposed for the feet. This actuator will be located in the foot of the robotic platform. Such a rotating foot will allow the entire robot to be turned on the spot in the range of ±90° (depending on the type of servo drive), which is not possible with conventional kinematic concepts and requires a much larger number of actuators for turning.

The final concept (Figure 8, 9) of the walking robotic platform would thus contain six actuators, and four of them rotary actuators would be located in the robot's feet. If the accumulators are also placed in the lower parts of the platform, then it will mean that the overall center of gravity of the robotic platform will be low and thus the robotic platform will have better stability when walking.

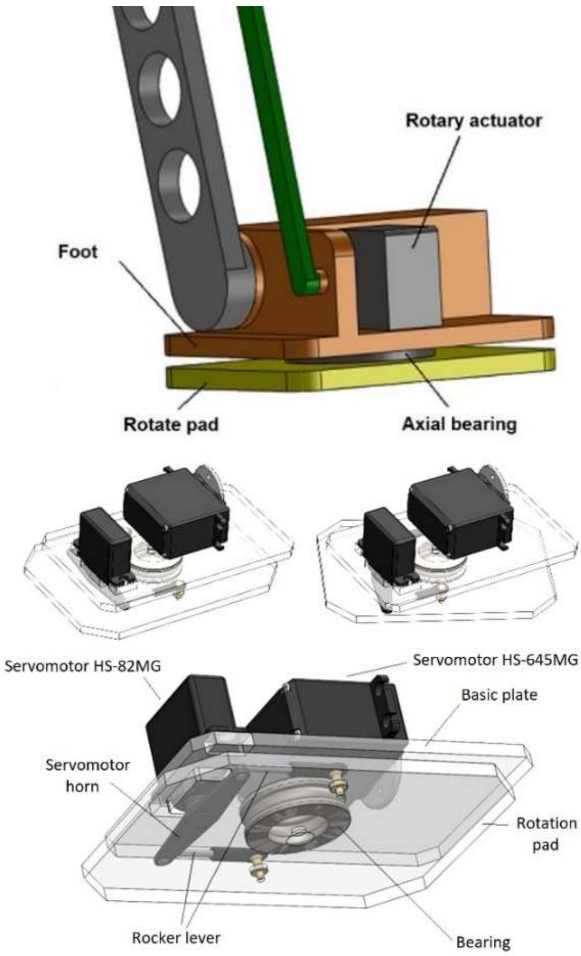

Figure 7 Rotating foot for changing walking direction

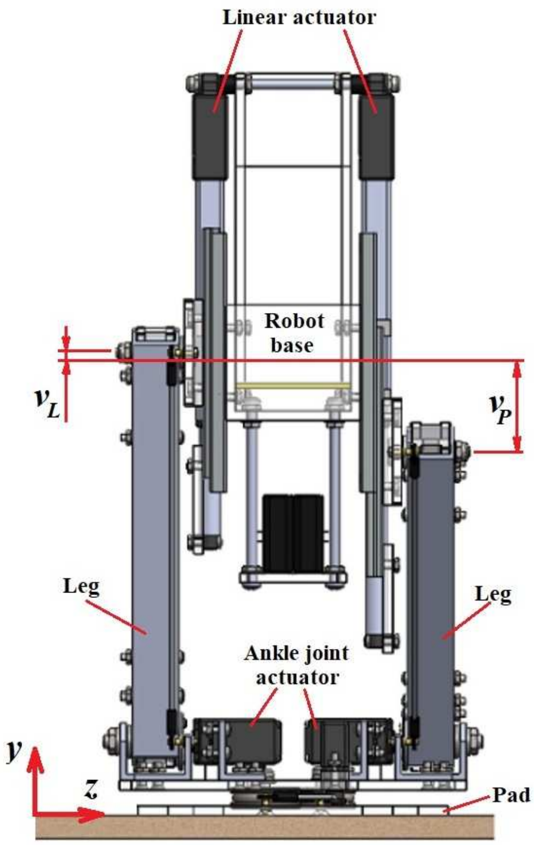

Figure 8 Final design of the walking robotic platform - front view

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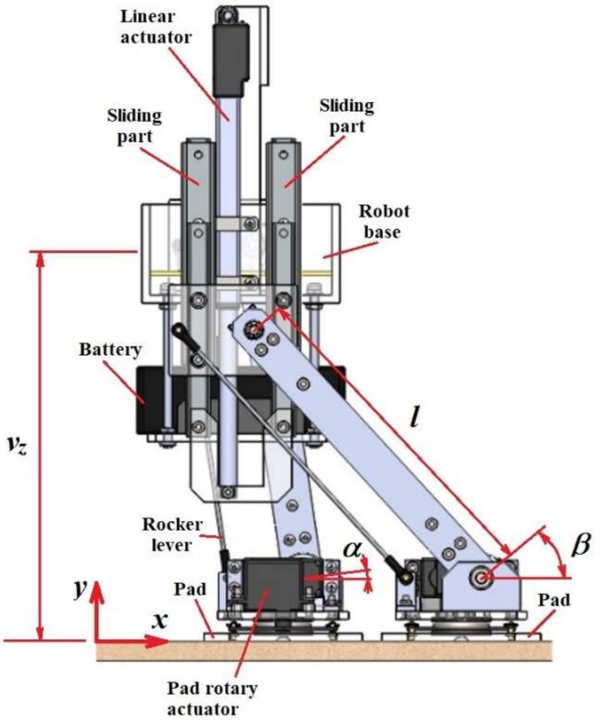

Figure 9 Final design of the walking robotic platform - side view

3 Simulations of the movement of the robotic platform

A mathematical model of the robotic platform was created from the proposed kinematics. The walking simulation confirmed the ability to walk for the proposed concept while also maintaining a stabilized vertical position (Figure 10, Figure 11). The ability to change the direction of walking is also important for the application of the structure for movement in space. The rotation of the robotic platform was simulated (Figure 12) and the results also confirm the usability of the proposed structure.

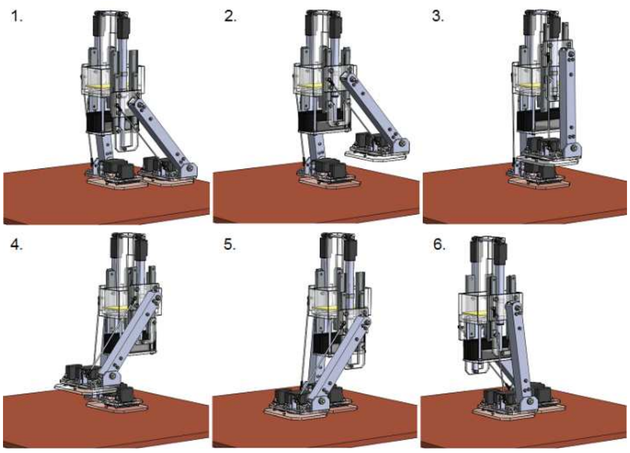

Figure 10 Walking simulation of the designed platform - CAD model

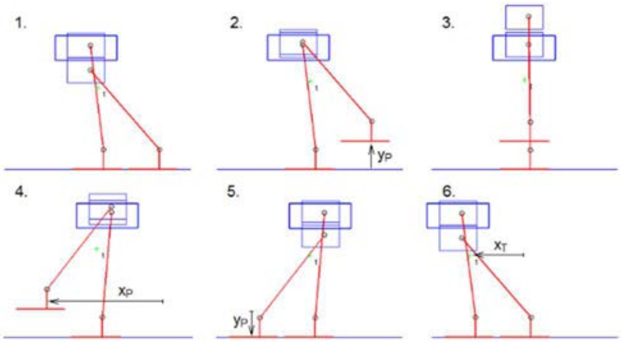

Figure 11 Simulation of walking of the proposed platform - math model

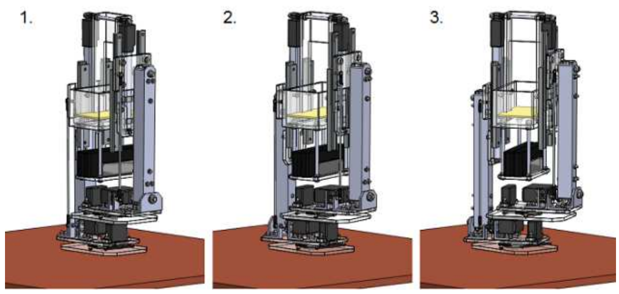

Figure 12 Simulation of the rotation of the designed platform

4 Conclusion

In the thesis, a robotic platform of a two-legged walking structure was designed, which can also be used for "bipedchair" applications as an alternative mobility solution for disabled people who have problems with walking. During the design, emphasis was placed on the minimum number of degrees of freedom and thus also the minimum number of actuators, which means minimum energy consumption. Energy consumption is also influenced by the kinematic arrangement of the platform itself. The proposed solution has unique properties, as it allows maintaining a stable vertical position of the base of the robotic platform, where a transported passenger could be placed at the same time. Simulations of the movement of the structure proved the correctness of the proposed solution.

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References

[1] KAHRAMAN, C., DEVECI, M., BOLTÜRK, E., TÜRK, S.: Fuzzy controlled humanoid robots: A literature review, *Robotics and Autonomous Systems*, Vol. 134, pp. 1-12, 2020. https://doi.org/10.1016/j.robot.2020.103643

[2] BROOKS, R.A., BREAZEAL, C., MARJANOVIĆ, M., SCASSELLATI, B., WILLIAMSON, M.M.: The Cog Project: Building a Humanoid Robot, In: Nehaniv C.L. (eds) Computation for Metaphors, Analogy, and Agents, CMAA 1998, Lecture Notes in Computer Science, Vol. 1562, Springer, Berlin, Heidelberg, 1999. https://doi.org/10.1007/3-540-48834-0_5

[3] WONG, C.C., CHENG, C.T., HUANG, K.H., YANG, Y.T.: Fuzzy control of humanoid robot for obstacle avoidance, *International Journal of Fuzzy Systems*, Vol. 10, No. 1, pp. 1-10, 2008. https://doi.org/10.30000/IJFS.200803.0001

[4] NISHIWAKI, K., SUGIHARA, T., KAGAMI, S., KANEHIRO, F., INABA, M., INOUE, H.: *Design and development of research platform for perception-action integration in humanoid robot: H6. Intelligent Robots and Systems*, 2000, IROS 2000, Proceedings, 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000) (Cat. No.00CH37113), 2000, pp. 1559-1564, Vol. 3, https://doi.org/10.1109/IROS.2000.895195

[5] OH, J.H., HANSON, D., KIM, W.S., HAN, Y., KIM, J.Y., PARK, I.W.: *Design of android type humanoid robot Albert HUBO*, Intelligent Robots and Systems, 2006, IEEE/RSJ, International Conference on Intelligent Robots and Systems, pp. 1428-1433, 2006. https://doi.org/10.1109/IROS.2006.281935

[6] PARK, H.Y., KIM, J.H., YAMAMOTO, K.: A New Stability Framework for Trajectory Tracking Control of Biped Walking Robots, *IEEE Transactions on Industrial Informatics*, Vol. 18, No. 10, pp. 6767-6777, 2022. https://doi.org/10.1109/TII.2021.3139909

[7] CHEN, H., CHEN, X., YU, Z., DONG, Ch., LI, Q., ZHANG, R., HUANG, Q.: *A Swing-foot Trajectory Generation Method For Biped Walking*, 2021, 6th IEEE International Conference on Advanced Robotics and Mechatronics (ICARM), 2021, pp. 841-845, 2021. https://doi.org/10.1109/ICARM52023.2021.9536057

[8] ROSA, N., LYNCH, K.M.: A Topological Approach to Gait Generation for Biped Robots, *IEEE Transactions on Robotics*, Vol. 38, No. 2, pp. 699-718, 2022. https://doi.org/10.1109/TRO.2021.3094159

[9] GAO, Z., CHEN, X., YU, Z., ZHU, M., ZHANG, R., FU, Z., LI, CH., LI, Q., HAN, L., HUANG, Q.: *Autonomous Navigation with Human Observation for a Biped Robot*, 2021 IEEE International Conference on Unmanned Systems (ICUS), 2021, pp. 780-785, 2021. https://doi.org/10.1109/ICUS52573.2021.9641391

[10] ZHU, X., WANG, L., YU, Z., CHEN, X., HAN, L.: *Motion Control for Underactuated Robots Adaptable to Uneven Terrain by De-composing Body Balance and Velocity Tracking*, 2021 6th IEEE International Conference on Advanced Robotics and Mechatronics (ICARM), 2021, pp. 729-734, 2021. https://doi.org/10.1109/ICARM52023.2021.9536090

[11] FEVRE, M., LIN, H., SCHMIEDELER, J.P.: *Stability and Gait Switching of Underactuated Biped Walkers*, 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019, pp. 2279-2285, 2019. https://doi.org/10.1109/IROS40897.2019.8967673

[12] SOBIRIN, M., HINDERSAH, H.: *Stability Control for Bipedal Robot in Standing and Walking using Fuzzy Logic Controller*, 2021 IEEE International Conference on Industry 4.0, Artificial Intelligence, and Communications Technology (IAICT), 2021, pp. 1-7, 2021. https://doi.org/10.1109/IAICT52856.2021.9532516

[13] YU, J., LI, C., GONG, D., ZUO, G., WANG, Y.: *Walking Simulation of Biped Robot on Inclined Plane Based on Gait Recognition*, 2020 IEEE International Conference on Real-time Computing and Robotics (RCAR), 2020, pp. 256-261, 2020. https://doi.org/10.1109/RCAR49640.2020.9303259

[14] SHIBATA, T., WADA, K.: Robot therapy: a new approach for mental healthcare of the elderly–a mini-review, *Gerontology*, Vol. 57, No. 4, pp. 378-386, 2011. https://doi.org/10.1159/000319015

[15] HUANG, S., TANIOKA, T., LOCSIN, R., PARKER, M., MASORY, O.: *Functions of a caring robot in nursing. Natural Language Processing and Knowledge Engineering (NLP-KE)*, 2011, 7th International Conference on Natural Language Processing and Knowledge Engi-neering, 2011, pp. 425-429, 2011. https://doi.org/10.1109/NLPKE.2011.6138237

[16] JYH-HWA, T., KUO, L.S.: *The development of the restaurant service mobile robot with a laser positioning system*, Control Conference, 2008, 27th Chinese Control Conference, 2008, pp. 662-666, 2008. https://doi.org/10.1109/CHICC.2008.4605839

[17] COLLINS, S.H., WIGGIN, M.B., SAWICKI, G.S.: Reducing the energy cost of human walking using an unpowered exoskeleton, *Nature*, Vol. 522, pp. 212-215, 2015. https://doi.org/10.1038/nature14288

[18] KONIAR, D., HARGAŠ, L., ŠTOFAN, S.: Segmentation of Motion Regions for Biomechanical Systems, *Procedia Engineering*, Vol. 48, pp. 304-311, 2012.

[19] LAN, C.W., LIN, S.S., KU, C.T., CHEN, B.S., LO, M.F., CHIEN, M.C.: *Design and Development of a Biped Robot for a Knee Exo-skeleton Analysis*, 2021 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS). 2021, pp. 1-2, 2021. https://doi.org/10.1109/ISPACS51563.2021.9650992

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[20] JATSUN, S., YATSUN, A., SAVIN, S., POSTOLNYI, A.: *Approach to motion control of an exoskeleton in "verticalization-to-walking" regime utilizing pressure sensors*, 2016 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), 2016, pp. 452-456, 2016. https://doi.org/10.1109/CYBER.2016.7574868

[21] LV, G., LIN, J., GREGG, R.D.: Trajectory-Free Control of Lower-Limb Exoskeletons Through Underactuated Total Energy Shaping, *IEEE Access*, Vol. 9, pp. 95427-95443, 2021. https://doi.org/10.1109/ACCESS.2021.3094979

[22] JACKSON, S., ELLIS, L., LUI, Co., MOLLOY, P., PATERSON, K., CHANDRAPAL, M., CHEN, X.Q.: *Development of an active powered biped lower limb exoskeleton*, 2014 IEEE International Conference on Au-tomation Science and Engineering (CASE), 2014, pp. 990-995, 2014. https://doi.org/10.1109/CoASE.2014.6899447

[23] GRIMMER, M., HOLGATE, M., HOLGATE, R., BOEHLER, A., WARD, J., HOLLANDER, K.,SUGAR, T., SEYFARTH, A.: A powered prosthetic ankle joint for walking and running, *BioMedical Engineering OnLine*, Vol. 15, Suppl 3, 2016. https://doi.org/10.1186/s12938-016-0286-7

[24] RASHID, A., MAHMOOD, A.: *Development and LQR Control of Prosthetic Leg Prototype for Human Gait*, 2019 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), 2019, pp. 1-5, 2019. https://doi.org/10.1109/ICECCE47252.2019.8940731

[25] ŠIMŠAJ, D.: *Design of a bipedal walking robot*, Technical University of Kosice, Faculty of Mechanical Engineering, Kosice, 2014.

[26] LIPTÁK, T., KELEMEN, M., GMITERKO, A., VIRGALA, I., HRONCOVÁ, D.: The Control of Holonomic System, *Acta Mechatronica*, Vol. 1, No. 2, pp. 15-20, 2016.

[27] KELEMENOVÁ, T., FRANKOVSKÝ, P., VIRGALA, I., MIKOVÁ, Ľ., KELEMEN, M., DOMINIK, L.: Educational models for mechatronic courses, *Acta Mechatronica*, Vol. 1, No. 4, pp. 1-6, 2016.

[28] VIRGALA, I., MIKOVÁ, Ľ., KELEMEN, M., HRONCOVÁ, D.: Snake-like robots, *Acta Mechatronica*, Vol. 3, No. 4, pp. 7-10, 2018. https://doi.org/10.22306/am.v3i4.43

[29] MIKOVÁ, Ľ., VIRGALA, I., KELEMEN, M.: Embedded systems, *Acta Mechatronica*, Vol. 3, No. 2, pp. 1-5, 2018. https://doi.org/10.22306/am.v3i2.32

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Design of PLC control system for cascading tanks controlling

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Keywords: PLC, HMI, control system, tank, pump, valve, sensor.
Abstract: The article deals with the design of a PLC control system for controlling cascade tanks in the technological process of liquid mixing. The mixing process is carried out automatically according to information from individual sensors. The system also includes elements for manual control of the technological system. A human machine interface system was designed to operate the system. The simulation showed the correctness of the designed system.

1 Introduction

The system (Figure 1) consists of three storage tanks A, B, C and one master tank. Liquids from storage tanks are fed into the master tank by solenoid valves according to the chosen procedure, where they are mixed and then discharged into the main collecting tank through the outlet valve. The goal is to prepare the concept of a control system for the automatic control of the technological process of preparation of liquid mixtures with the possibility of service intervention in the process in case of emergency shutdown of the system or manual switching on of some part of the system in the event of a malfunction. The proposed reservoir management system will be used for didactic purposes for the practical education of students [1-17].

Reed switch float level sensors are designed to detect the level of liquids in each tank. Solenoid valves are designed for the discharge of liquids by gravity discharge from the tank. Low-voltage pumps are designed for pumping liquids (Figure 2). The process of mixing liquids in the master tank will take place for 10 seconds, and then the resulting mixture is discharged into the collection tank.

Options for alternative solutions to the process can be changed and set according to the selected recipe.

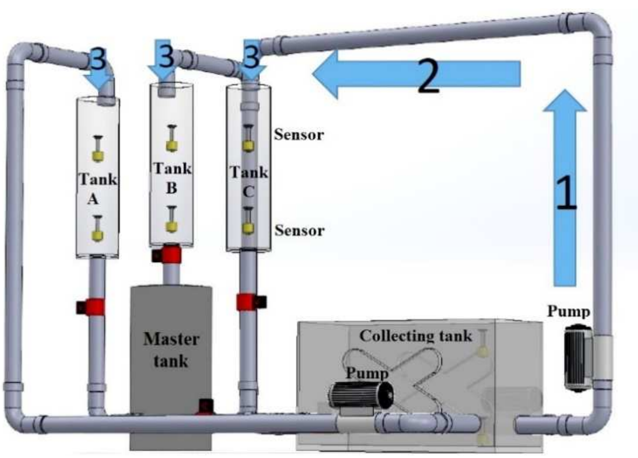

Figure 1 Educational model layout design

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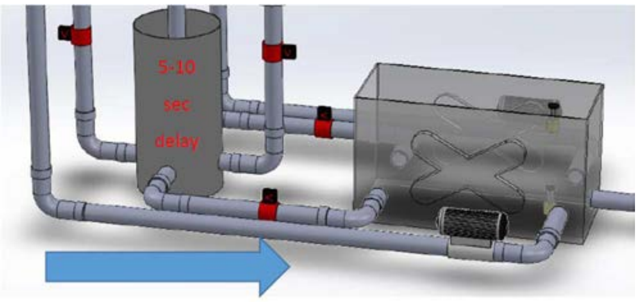

Figure 2 Simulation of fluid mixing and discharge of fluid into the tank

2 Control system design

The proposed diagram (Figure 3) shows the location of individual sensors, solenoid valves and pumps in the proposed system concept. The connection of individual components in the system is designed using transparent hoses.

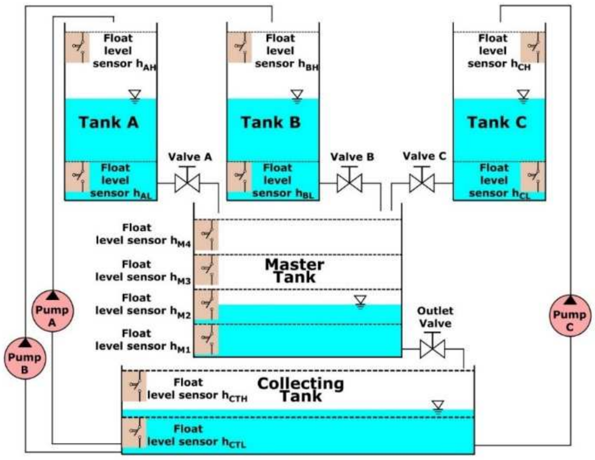

Figure 3 The diagram of the system

After solving design problems, selecting components, and describing the principle of the system, you need to choose a control element that will program the system for the work we need. The PLC will act as such a control element. Programmable logic controller (PLC) is an electronic device used to automate technological processes such as conveyor line control, pumps at water supply stations, numerically controlled machines, etc. In essence, it is a real-time hardware-software system - a computer designed to run a real-time operating system and applications that implement the necessary algorithms. Its main difference from general-purpose computers is the large number of input/output devices for sensors and actuators, as well as the ability to work reliably in adverse conditions: wide temperature range, high humidity, strong electromagnetic interference, vibration and more.

PLCs have a number of features that distinguish them from other electronic devices used in production:

- Unlike a microcontroller (single-chip computer), a chip designed to control electronic devices, a PLC is a stand-alone device, not a separate chip.
- Unlike computers focused on decision-making and operator management, PLCs are focused on working with machines through an extensive I/O system for inputting sensor signals and outputting signals to actuators.
- In contrast to built-in PLC systems, they are manufactured as stand-alone products, separate from the equipment controlled by it.

Siemens TIA Portal software (Figure 4) will be used to program the controller for our wishes. TIA Portal (Totally Integrated Automation Portal) is an integrated software development environment for process automation systems from the level of drives and controllers to the level of human-machine interface.

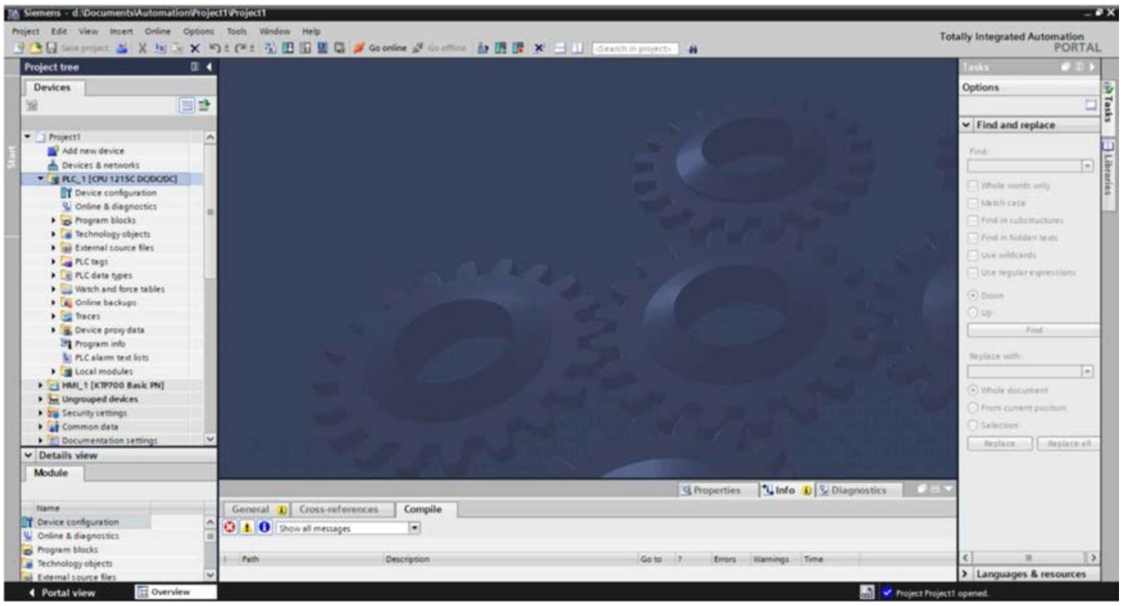

Figure 4 TIA Portal Workspace

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It is the embodiment of the concept of integrated automation (Eng. Totally Integrated Automation) and the evolutionary development of the Simatic family of automation systems from Siemens AG.

Development of projects for controllers and distributed I/O devices, configuration of human-machine interface systems and SCADA systems, parameterization of network components and communication modules, debugging of software control algorithms, as well as commissioning of drives - all this is combined into a common software structure and have a unified user interface. This not only speeds up work, but also allows you to create transparent solutions that are easy to maintain and diagnose and can be easily expanded or transformed.

Variables or tags must be stored before creating the program itself. In essence, this is the identification of the actual inputs and outputs in the system that will operate the PLC. Using Image 30 you can see all the main devices that will be connected to the PLC. Sensors are inputs, and solenoid valves and pumps are outputs. Using this, you can create tags for the program.

To simulate the system before connecting it, the physical inputs must be set as memory to be able to change them and simulate possible situations in the system (Figure 5).

Level sensors are designed for the concept of this system, which generate a logic level High when the liquid level exceeds the location of this sensor and generate a logic level Low when the liquid level drops below the location of this sensor. The opening of all solenoid valves will be realized by setting the logic level High, and the closing will be realized by setting the logic level Low.

Default tag table

	Name	Data type	Address	Retain	Acces...	Writa...	Visibl...	Comment
1	Pump A	Bool	%Q0.0	☐	☑	☑	☑	
2	Pump B	Bool	%Q0.1	☐	☑	☑	☑	
3	Pump C	Bool	%Q0.2	☐	☑	☑	☑	
4	Valve A	Bool	%Q0.3	☐	☑	☑	☑	
5	Valve B	Bool	%Q0.4	☐	☑	☑	☑	
6	Valve C	Bool	%Q0.5	☐	☑	☑	☑	
7	Outlet valve	Bool	%Q0.6	☐	☑	☑	☑	
8	Float level sensor hAH	Bool	%M0.0	☐	☑	☑	☑	
9	Float level senzor hAL	Bool	%M0.1	☐	☑	☑	☑	
10	Float level sensor hBH	Bool	%M0.2	☐	☑	☑	☑	
11	Float level sensor hBL	Bool	%M0.3	☐	☑	☑	☑	
12	Float level sensor hCH	Bool	%M0.4	☐	☑	☑	☑	
13	Float level sensor hCL	Bool	%M0.5	☐	☑	☑	☑	
14	Float level sensor hM1	Bool	%M0.6	☐	☑	☑	☑	
15	Float level sensor hM2	Bool	%M0.7	☐	☑	☑	☑	
16	Float level sensor hM3	Bool	%M1.0	☐	☑	☑	☑	
17	Float level sensor hM4	Bool	%M1.1	☐	☑	☑	☑	
18	Float level sensor hCTH	Bool	%M1.2	☐	☑	☑	☑	
19	Float level sensor hCTL	Bool	%M1.3	☐	☑	☑	☑	
20	<Add new>			☐	☑	☑	☑	

Figure 5 PLC tags

After identifying the tags, you can start writing the program. FBD (Function Block Diagram) was chosen as the programming language for this project. For better orientation in the program it can be divided into networks, each of which will correspond to the tanks.

3 Concept of function block diagram networks

Network 1: Total Start Stop (Figure 6) is designed for total program control. The network contains the "Set/reset flip-flop" (SR flip/flop) instruction to set or reset the bit of a specified operand based on the signal state of the inputs S and R1. If the signal state is "1" at input S and "0" at input R1, the specified operand is set to "1". If the signal state is "0" at input S and "1" at input R1, the specified operand will be reset to "0". Input R1 takes priority over input S. When the signal state is "1" on both inputs S and R1, the signal state of the specified operand is reset to "0".

In this network 1, it contains two inputs, while the "START" input causes the system to be fully turned on, and the "STOP" input represents the system to be completely turned off. In other networks, the output from this block "Startup" will be incorporated so that this block of network 1 enables absolute control over all systems and enables a safe shutdown of the system and then a restart to the last known configuration. This network 1 will therefore be the superior system for other networks.

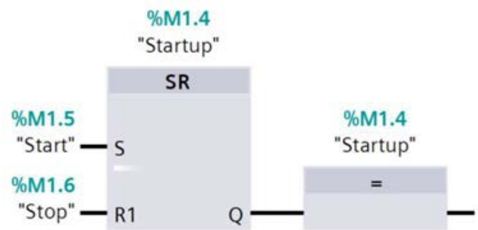

Figure 6 Network 1: Total Start Stop

Network 2: Controlling of Pump A (Figure 7) also contains an SR flip/flop block for switching on or off of pump A. For switching on, the signal "Float level sensor

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hAL" is used, which signals that the liquid level is below the level of this sensor and using the logic level LOW starts the SR block and turns on pump A, but only if at the same time the superior system "Startup" is in the state of logic level HIGH". Resetting the SR block and thus turning off pump A is possible when the liquid level reaches the level of the sensor "Float level sensor hAH " and that, using the logic level HIGH, causes pump A to be turned off. Or pump A can be turned off using the superior system "Startup" from network 1.

An additional block "estop pump A" was added to network 2, which is created using an RS flip/flop block for independently safely turning off pump A.

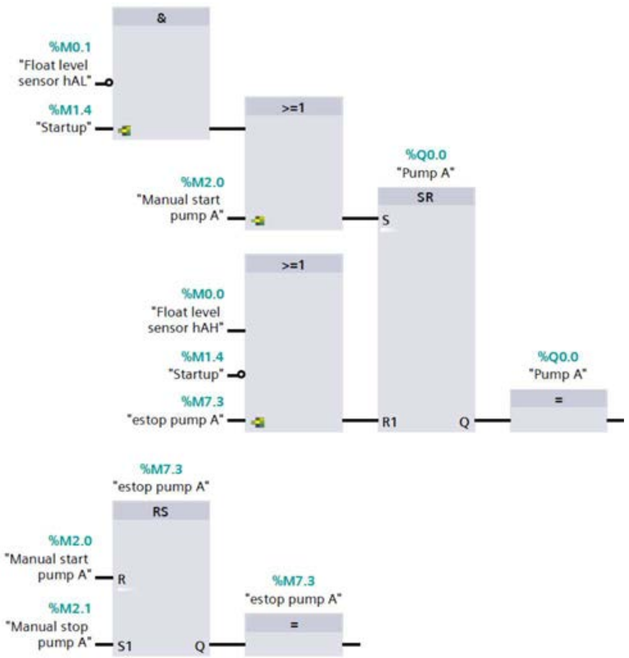

Figure 7 Network 2: Controlling of Pump A

Network 3: Controlling of Pump B (Figure 8) and Network 4: Controlling of Pump C (Figure 9): Controlling of Pump C are similar to network 2. The operation of pump B is connected to the sensor "Float level sensor hBL" and to the sensor "Float level sensor hBH". The operation of pump C is connected to the sensor "Float level sensor hCL" and to the sensor "Float level sensor hCH". Both of these networks are conditioned by the superior system from network 1 "Startup".

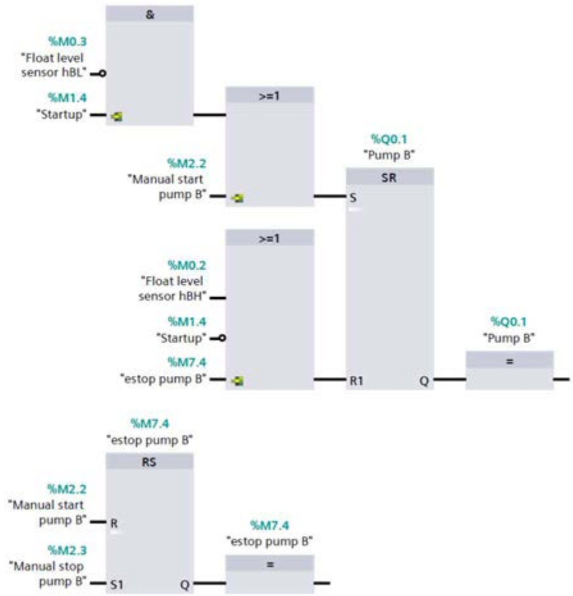

Figure 8 Network 3: Controlling of Pump B

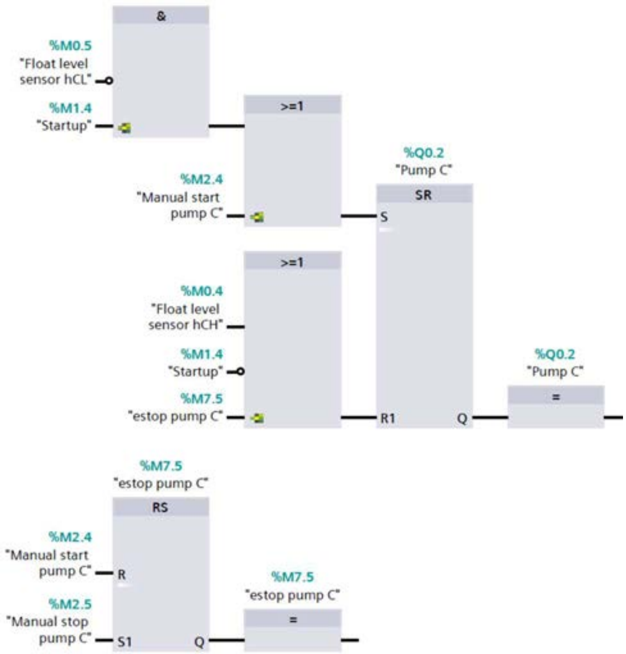

Figure 9 Network 4: Controlling of Pump C

Network 5: Filling of Master Tank with fluid A using the valve A (Figure 10) **-** solves the filling of the master tank with fluid from tank A, while this filling is carried out using valve A only if the fluid in tank A is between the levels of the fluid level detected by the level sensors" Float level sensor hM1" and "Float level sensor hM2". However, this process can only take place if there is at least a minimum amount of liquid level in tank A at the level of the "Float level sensor hAL" sensor. In the same way, the operation of valve A is conditioned by the superior system "Startup" from network 1. Another condition for starting valve A is that the master tank was completely emptied

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after the previous filling to below the level of the "Float level sensor hM1" sensor. Network 5 is also supplemented with another RS flip/flop block "estop valve A", which is used to create the possibility of emergency shutdown of valve A independently of other devices.

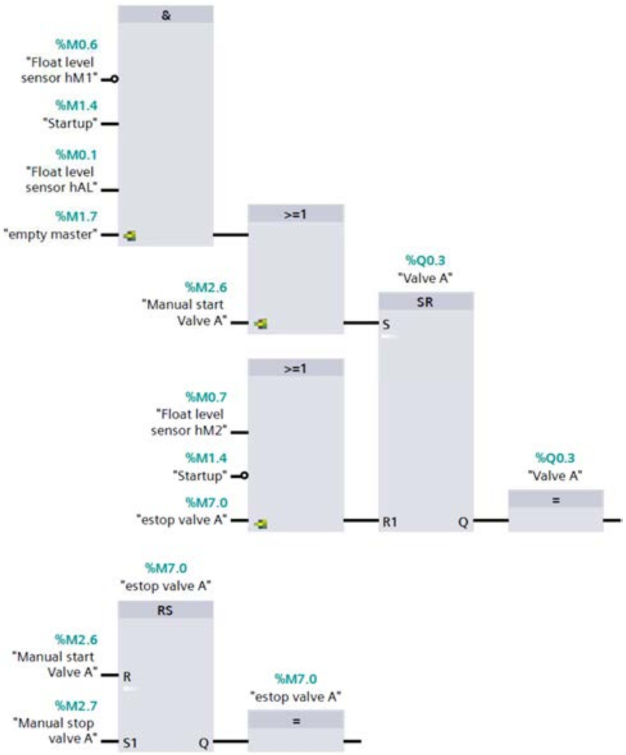

Figure 10 Network 5: Filling of Master Tank with fluid A using the valve A

<u>Network 6: Filling of Master Tank with fluid B using the valve B</u> (Figure 11) - is implemented analogously to network 5. However, in this network valve B is started for filling fluid from tank B to the master tank between the level levels detected by the sensors "Float level sensor hM2" and "Float level sensor hM3". Also, this valve B can only be started if the superior system "Startup" is active and the master tank has been previously drained. Valve B can also be started only if the liquid in tank B is at least above the level of the "Float level sensor hBL" sensor. Also in this network, an RS flip/flop block for emergency shutdown of this valve B "estop valve B" is added.

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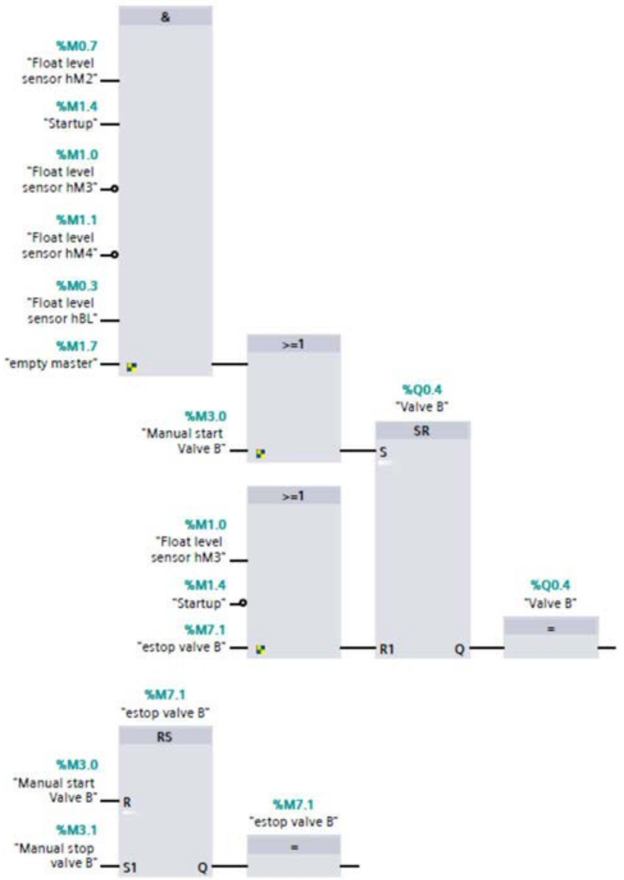

Figure 11 Network 6: Filling of Master Tank with fluid B using the valve B

<u>Network 7: Filling of Master Tank with fluid C using the valve C</u> (Figure 12) - is created for filling the master tank with fluid from tank C between the levels of the sensors "Float level sensor hM3" and "Float level sensor hM4" in the master tank. This process can only be carried out if there is at least a minimum amount of liquid in tank C above the level of the "Float level sensor hCL" sensor and the master tank volume has previously been completely emptied, which is signalled by the "empty master" tag. Also in this network, the "estop valve C" block is added for the emergency shutdown of valve C.

<u>Network 8: Empty Master tank</u> (Figure 13) - it should leave the filled mixture of liquids for 10 seconds and then the entire contents of the master tank should be drained into the collecting tank by activating the "Outlet valve". "Outlet valve is deactivated only after a time of 1 second has elapsed after the master tank is completely drained below the level of the lowest sensor "Float level sensor hM1". Just like the previous networks, in this network also the block "estop outlet valve" is added for the emergency shutdown of the "Outlet valve".

<u>Network 9: Master Tank status</u> (Figure 14) - is used to detect the status of the master tank. For the proper functioning of the entire system, it is necessary to know when the master tank was completely emptied, and this

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information is stored in the "empty master" tag. After emptying the master tank, the entire filling process can be restarted again.

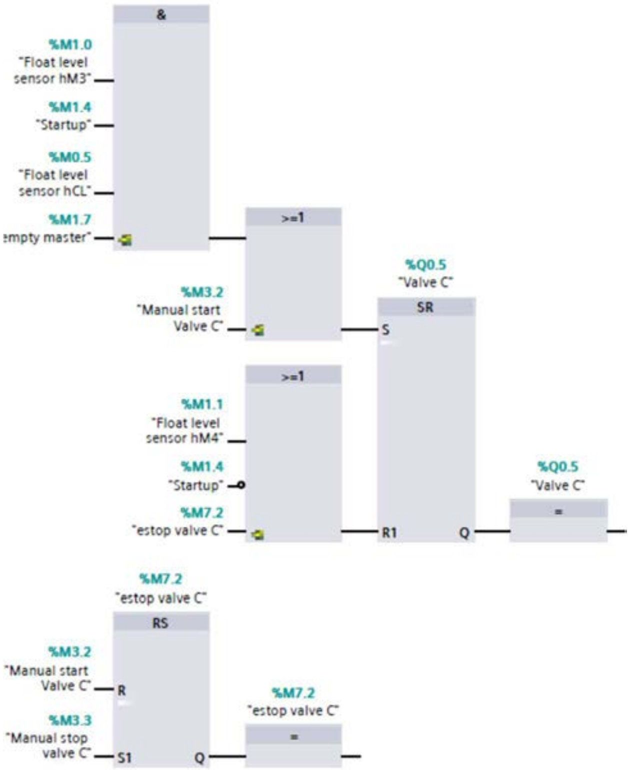

Figure 12 Network 7: Filling of Master Tank with fluid C using the valve C

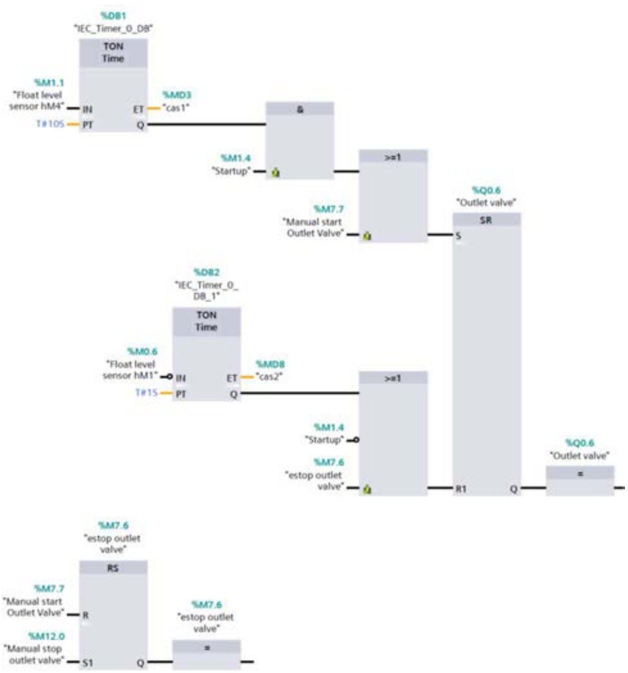

Figure 13 Network 8: Empty Master tank after 10 seconds

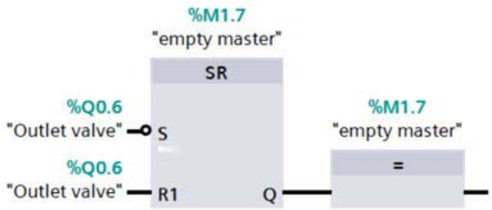

Figure 14 Network 9: Master Tank status

4 Process visualization and control using the HMI interface

The HMI (Human machine interface) interface allows you to create a user interface for controlling the system by the operator and also for visualizing the current status of all subsystems. The operator can thus fully control the system remotely and monitor all its activities. When switched off, pipes and individual valves and pumps are shown in gray (Figure 15). After the system is turned on, the active parts are displayed in blue. Active sensors also have an indicator LED for displaying the status of the sensors (Figure 16).

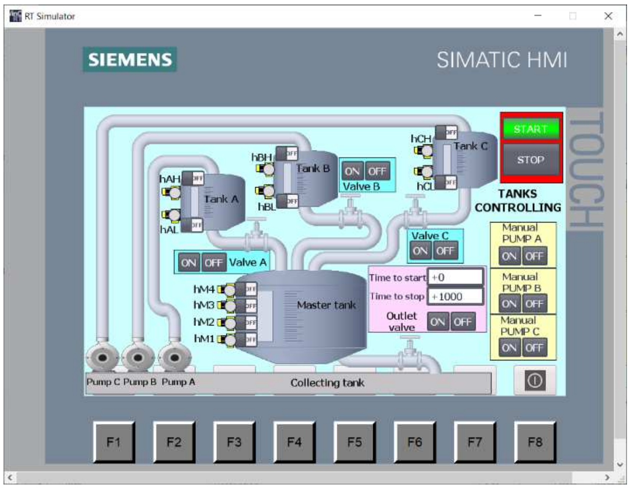

Figure 15 System in off state

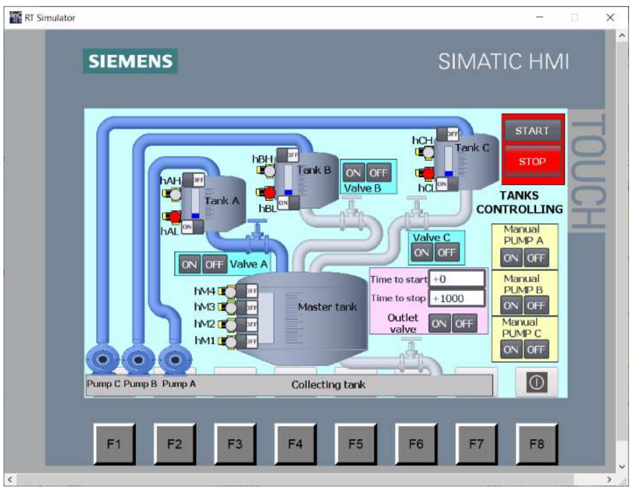

Figure 16 Filling tanks A, B, C

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In addition, the HMI is supplemented with an emergency shutdown of all systems or individual systems can be shut down individually.

The filling and draining of fluids are also indicated by status indicators with a dark blue colour (Figure 17). To display the discharge progress of the master tank, a time indication of the discharge progress is also added.

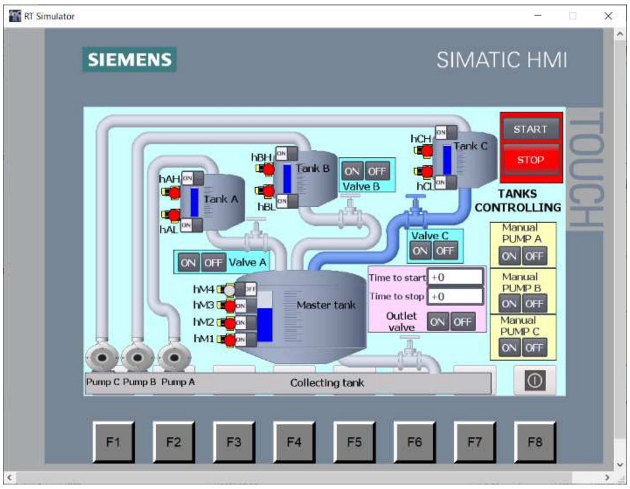

Figure 17 Filling the master tank

5 Conclusion

In this work, the concept of controlling cascading tanks for mixing liquids in the technological process according to the chosen procedure was proposed. Individual filling and emptying is controlled automatically according to the status of individual sensors. All action subsystems such as pumps and valves can be turned off in an emergency with one button or separately with special buttons. In the next work, the diagnostic network for detecting fault conditions of individual subsystems will be solved, and the possibility of flexible change of the mixing procedure of the mixture by changing the order of liquid dosing and changing the amount of liquid dosing will be proposed. This will enable a flexible change in the proportions of the mixed mixture of liquids according to the operator's current requirements.

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References

[1] LANDER, A.: *Programmable Logic Controllers: The Evolution of a Disruptive Technology*, Engineering.com, [Online], Available: https://new.engineering.com/story/programmable-logic-controllers-the-evolution-of-a-disruptive-technology [26 May 2021], 2021.

[2] SIMATIC S7-1200 *Getting started with S7-1200*, [Online], Available: https://cache.industry.siemens.com/dl/files/875/39644875/att_76194/v1/s71200_getting_started_en-US_en-US.pdf?download=false [26 May 2021], 2021.

[3] SIMATIC S7-1200 *Programming Guideline for S7-1200/1500*, [Online], Available: https://assets.new.siemens.com/siemens/assets/api/uuid:c7de7888-d24c-4e74-ad41-759e47e4e444/Programovani-S7-1200-1500-2018.pdf [26 May 2021], 2021.

[4] KELEMEN, M., SINČÁK, P.J.: Programmable logic controller training stands for educational purposes, *Technical Sciences and Technologies*, Vol. 21, No. 3, pp. 274-280, 2020.

[5] KELEMEN, M., LIGUŠOVÁ, J., LIGUŠ, J., MAXIM, V.: Additional Modules for Programmable Logic Controller Based Training Stands, *Technical Sciences and Technologies*, Vol. 22, No. 4, pp. 170-176, 2020.

[6] KELEMEN, M., KELEMENOVÁ, T., VIRGALA, I., PRADA, E., MIKOVÁ, Ľ., HRONCOVÁ, D., VARGA, M., SINČÁK, P. J.: *Training stations with programmable logic controllers*, In: Technological Forum 2021, 12th International technical conference, 30.6. - 02.07.2021, Jaroměř, ČR, pp. 117-121, 2021.

[7] VITKO, A., JURIŠICA, L., KĽÚČIK, M., MURÁR, R., DUCHOŇ, F.: Embedding Intelligence into a Mobile Robot, *AT&P Journal Plus*, Vol. 2008, No. 1, Mobile robotic systems, pp. 42-44, 2008.

[8] BOŽEK, P.: Robot path optimization for spot welding applications in automotive industry, *Tehnicki vjesnik / Technical Gazette*, Vol. 20, No. 5, pp. 913-917, 2013.

[9] DUCHOŇ, F., BABINEC, A., KAJAN, M., BEŇO, P., FLOREK, M., FICO, T., JURIŠICA, L.: Path planning with modified a star algorithm for a mobile robot, *Procedia Engineering*, Vol. 96, pp. 59-69, 2014.

[10] PÁSZTÓ, P., HUBINSKÝ, P.: Mobile robot navigation based on circle recognition, *Journal of Electrical Engineering*, Vol. 64, No. 2, pp. 84-91, 2013.

[11] ABRAMOV, I.V., NIKITIN, Y.R., ABRAMOV, A.I., SOSNOVICH, E.V., BOŽEK, P.: Control and Diagnostic Model of Brushless DC Motor, *Journal of Electrical Engineering*, Vol. 65, No. 5, pp. 277-282, 2014.

[12] KONIAR, D., HARGAŠ, L., ŠTOFAN, S.: Segmentation of Motion Regions for Biomechanical Systems, *Procedia Engineering*, Vol. 48, pp. 304-311, 2012.

[13] VIRGALA, I., MIKOVÁ, Ľ., KELEMEN, M., HRONCOVÁ, D.: Snake-like robots, *Acta Mechatronica*, Vol. 3, No. 4, pp. 7-10, 2018. https://doi.org/10.22306/am.v3i4.43

[14] MIKOVÁ, Ľ., VIRGALA, I., KELEMEN, M.: Embedded systems, *Acta Mechatronica*, Vol. 3, No. 2, pp. 1-5, 2018. https://doi.org/10.22306/am.v3i2.32

[15] KELEMENOVÁ, T., FRANKOVSKÝ, P., VIRGALA, I., MIKOVÁ, Ľ., KELEMEN, M., DOMINIK, L.: Educational models for mechatronic courses, *Acta Mechatronica*, Vol. 1, No. 4, pp. 1-6, 2016.

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[16] LIPTÁK, T., KELEMEN, M., GMITERKO, A., VIRGALA, I., HRONCOVÁ, D.: THE CONTROL OF HOLONOMIC SYSTEM, *Acta Mechatronica*, Vol. 1, No. 2, pp. 15-20, 2016.

[17] KURYŁO, P., PIVARČIOVÁ, E., CYGANIUK, J., FRANKOVSKÝ, P.: Machine vision system measuring the trajectory of upper limb motion applying the Matlab software, *Measurement Science Review*, Vol. 19, No. 1, pp. 1-8, 2019.

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An overview of the kinematics and workspace of robots with different structures

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Keywords: kinematic analysis and forward kinematics, workspace, joint, kinematics chain and arm of robot, effector.
Abstract: Robotics is gaining an important place in many areas of industrial production nowadays. With the growing number of robots in production, we are coming to the solution of various tasks to ensure their optimal activity when handling objects or during other technological activities. These are tasks such as planning its movement, planning the robot's trajectory, navigation and tracking the movement of the end member. In this article, we will deal with the issue of robot workspace structures and determining the robot workspace of a specific robot model.

1 Introduction

The development of robots and manipulators belongs to the complex development process of entire mechanical engineering, electrical engineering and many other fields as their inseparable part. Extending the handling capabilities requires the development of new types of kinematic structures, not only of individual types of manipulators, but also of entire handling systems [1-3].

Assessing industrial robots and manipulators requires to distinguish between the mechanical part and the part formed by the control system. A characteristic feature of the mechanical part is the kinematic structure, which significantly affects the basic properties of robots and manipulators, especially the size and shape of the handling and working space.

Currently we have experience with the wide application of industrial automated robotic workstations used mainly for assembly purposes in many manufacturing companies. This results in the need to control an industrial robot in a defined space. The robot mechanism is mostly an open kinematic chain. In the case of a mechanical system of industrial robots used in the production process, this mechanism can have 3 or more degrees of freedom of movement, which depends on the specific robot. In this article, we will focus on the kinematic analysis of manipulator and robot mechanisms. We need to track the position of the working member of the manipulator relative to the inertial coordinate system. Using matrix methods in kinematics, we can determine the position of the end member of the monitored desired working member of the robot. We solve the inverse and forward kinematics. We are also interested in the workspace in which the robot moves during its work. The presented article is dedicated to this issue [4-7].

2 Kinematic structure of robot mechanisms

The basic structure of the robot is an open kinematic chain. Alternatively, the chain can also contain a closed loop of members, it will be a kinematic chain with a closed loop. The point of connection of two links is called a kinematic pair. The mobility of the members connected to each other is ensured by joints. Articulation between connected members is realized using a prismatic or rotary joint. The prismatic joint enables the translational movement of the members connected to each other. The rotary joint enables mutual rotation of the members in the joint. Rotary kinematic pairs are preferred over translational ones for compactness and reliability [6].

Our aim is to position and orientation an object in three-dimensional space. We require six degrees of freedom in space, three for the location of a point on the object and three for the orientation of the object relative to the reference coordinate system. If we have more degrees of freedom than necessary, we speak of a kinematically redundant manipulator.

The workspace represents the part of the environment where the end effector of the manipulator can reach. Its shape and volume also depend on the design of the manipulator as well as on the presence of mechanical constraints of the bonds. The task required of the arm is to

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position the wrist, which is then required to orient the end effector; then at least three degrees of mobility in a three-dimensional workspace are required. The type and sequence of degrees of mobility of the arm, starting from the base joint, allows manipulators to be classified as: cartesian, cylindrical, spherical, SCARA and anthropomorphic [1-7].

3 The configuration of robotic structures

Moving a person from one place to another is a task often solved by a person. In robotics, planning the path along which the working member will move is one of the basic tasks. In robotics, for example, we are looking for the path of a robotic arm or the path of a mobile service robot from the starting position to the target position. During its work, the robot moves in the workspace, which is determined by the possibilities of its joint variables. The types of workspaces are related to the configuration of robotic structures. Their overview is shown in Fig. 1 a) to Fig. 1 d) [7]. The designation of joints in the description of the picture is P - prismatic joint with translational motion, R – rotational joint, with rotational motion [6-7].

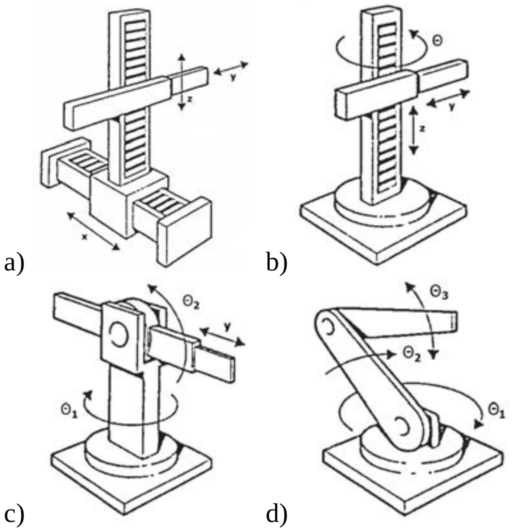

Figure 1 Mechanical structures of robots a) cartesian PPP structure, b) cylindrical RPP structure, c) polar RRP structure, d) universal RRR structure [7]

3.1 *Cartesian geometry of robot*

Cartesian geometry is realized by three prismatic links, the axes of which are typically perpendicular to each other (Fig. 2 a). Due to the simple geometry, each degree of mobility corresponds to a degree of freedom in Cartesian space, so it is natural to make direct movements in space. For a Cartesian manipulator, the joint variables are the Cartesian coordinates of the end effector relative to the base (Fig. 2 b).

The Cartesian structure offers very good mechanical stiffness. The accuracy of wrist positioning is constant in each working space, which is the volume bounded by a rectangular prism (Fig. 2 a). The workspace of the Cartesian manipulator is also shown in Fig. 2 c). An example of a Cartesian robot from Epson-Seiko is shown in Fig. 2 d) [6-7].

In contrast to the high precision, the design has low dexterity because all the joints are prismatic. The approach to handling the object is lateral. On the other hand, if it is desired to approach the object from above, a Cartesian manipulator can be implemented using a gantry structure, as shown in Fig. 2 e). Such a structure makes it possible to obtain a large volume workspace and to handle objects of large dimensions and weight.

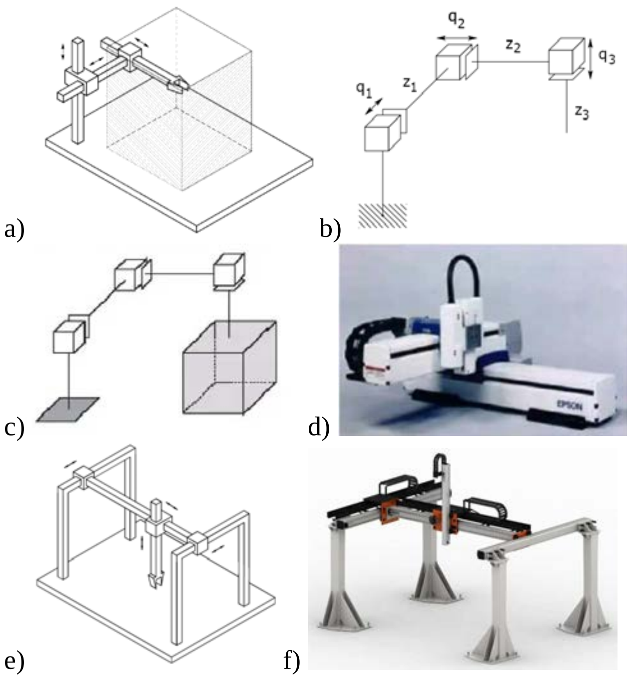

Figure 2 The Cartesian structure of robots with prismatic joints PPP a) kinematic structure and workspace, b) kinematic scheme with generalized coordinates of the kinematic pairs $q_1=d_1$, $q_2=d_2$, $q_3=d_3$, c) workspace of the kinematic structure, d) the Epson Cartesian Robot, e) gantry manipulator [1-7], f) gantry manipulator with 3 axis linear module [14]

Cartesian manipulators are used for material handling and assembly. The joint control of the Cartesian manipulator motors is typically electric and occasionally pneumatic [1-7].

3.2 *Cylindrical geometry of robot*

The cylindrical geometry of the cylindrical manipulator RPP differs from the Cartesian one in that the first prismatic joint is replaced with a revolute joint (Fig. 3 b). If the task is described in cylindrical coordinates, also in this case each degree of mobility corresponds to a degree of freedom. The cylindrical structure offers good mechanical stiffness. Wrist positioning accuracy decreases as the horizontal stroke increases. The workspace is a portion of a hollow cylinder (Fig. 3 a). The horizontal prismatic joint makes the wrist of a cylindrical manipulator

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suitable to access horizontal cavities. Cylindrical manipulators are mainly employed for carrying objects even of gross dimensions, in such a case the use of hydraulic motors is to be preferred to that of electric motors.

Cylindrical robots operate in a cylindrical-shaped work environment and have at least one rotary axis at the base and one or more prismatic (linear) axes [1-7].

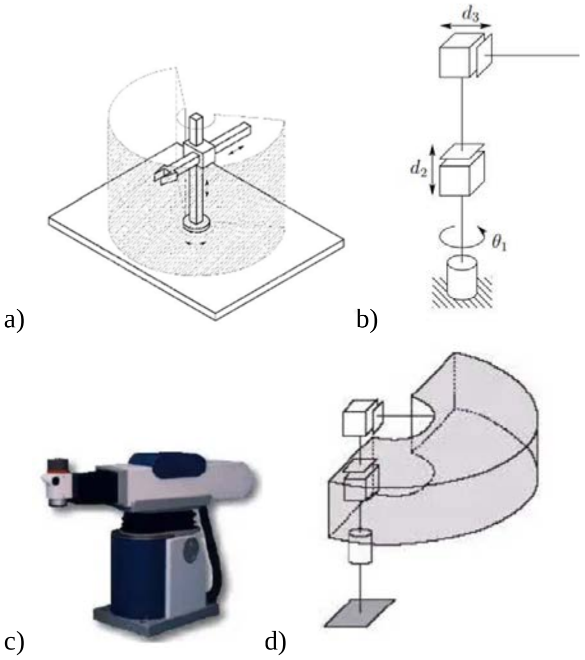

Figure 3 Cylindrical structure of robots a) kinematic structure RPP, b) generalized coordinates of the kinematic pairs are $q_1=\theta_1$, $q_2=d_2$, $q_3= d_3$, c) the Seiko RT 3300 Robot d) workspace of the cylindrical manipulator [1-7]

3.3 Spherical geometry of robot RRP

The spherical manipulator RRP differs from the cylindrical one in that the second prismatic joint is replaced with a revolute joint (Fig. 4 a).

Mechanical stiffness is lower than the above two geometries (cartesian and cylindrical) and mechanical construction is more complex. The workspace is a portion of a hollow sphere (Fig. 4 d), it can also include the supporting base of the manipulator and thus it can allow manipulation of objects on the floor. Spherical manipulators are mainly employed for machining. Electric motors are typically used to actuate the joints. Figure 4 e)-f) shows the Stanford arm. They are used in welding, pressure casting and injection or extrusion machines [1-7].

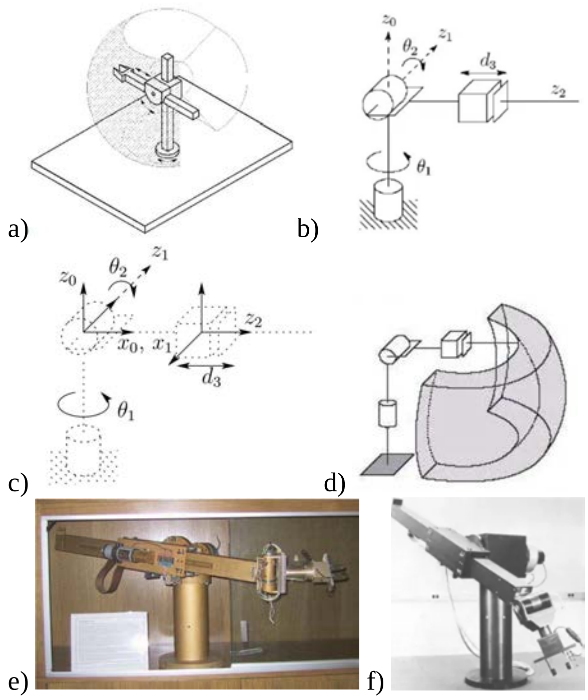

Figure 4 Spherical structure of robots a) kinematic structure RRP, b) generalized coordinates of the kinematic pairs are $q_1=\theta_1$, $q_2=\theta_2$, $q_3=d_3$, c) kinematic scheme of RRP structure, d) workspace of RRP structure, e)-f) Stanford Arm [1-7]

3.4 Scara manipulator

A special is the SCARA structure that can be realized by disposing two revolute joints and one prismatic joint in such a way that all the axes of motion are parallel (Fig. 5 b). The acronym SCARA stands for Selective Compliance Assembly Robot Arm and characterizes the mechanical features of a structure offering high stiffness to vertical loads and compliance to horizontal loads. As such, the SCARA structure is congenial to vertical assembly tasks. Wrist positioning accuracy decreases as the distance of the wrist from the first joint axis increases. The typical workspace is illustrated in Fig. 5 a). The SCARA manipulator is suitable for manipulation of small objects; joints are actuated by electric motors [1-7].

SCARA are often used in assembly operations. They vary on the cylindrical design and have two parallel axes that provide movement in one plane.

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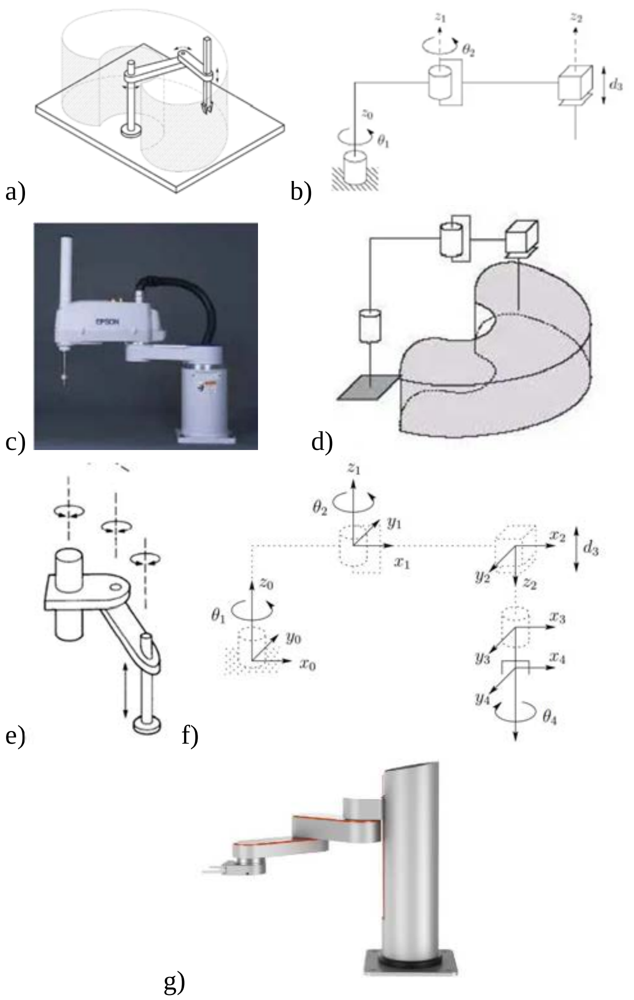

Figure 5 Scara structure of robots a) kinematic structure RRP and workspace, b) generalized coordinates with $q_1 = \theta_1$, $q_2 = \theta_2$, $q_3 = d_3$, c) Epson E2L653S Scara Robot, d) RRP structure and workspace e) kinematic structure RRRP, f) Scara manipulator structure RRPR, g) Scara manipulator structure PRRR [1-7]

3.5 *Articulated configuration of robots RRR*

The articulated configuration is realized by three revolute joints, the axis of the first joint is orthogonal to the axes of the other two, which are parallel (Fig. 6 b). Based on its similarity to the human shoulder, the second joint is called the shoulder joint and the common joint is called the elbow joint, which connects the "arm" to the "forearm". The articulated structure is the cleverest, as all the joints are rotatable. The accuracy of wrist positioning varies within the workspace. In Fig. 6 a) is the working space part of the sphere [1-7].

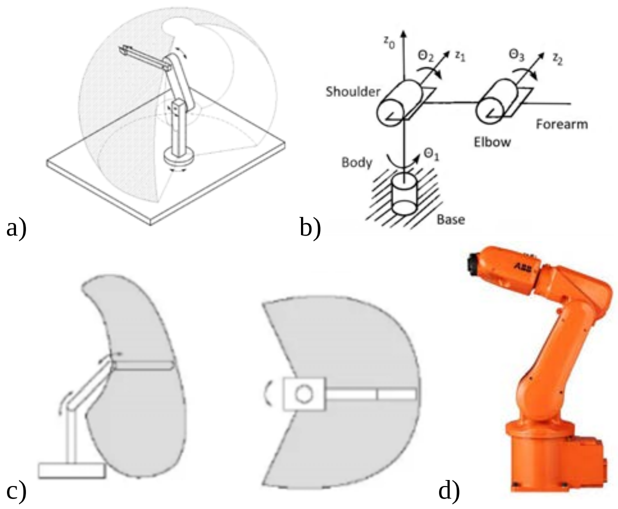

Figure 6 Articulated configuration of robots a) kinematic structure RRR and workspace, b) generalized coordinates $q_1 = \theta_1$, $q_2 = \theta_2$, $q_3 = \theta_3$, c) workspace of the manipulator, d) ABB IRB 120 Robot [1-7]

The joints are usually powered by electric motors. The range of industrial applications of articulated manipulators is wide [1-9].

3.6 *Parallel manipulator*

Parallel manipulator has two or more independent kinematics chains which are connecting the base to the end-effector (Fig. 7).

A parallel robot with six degrees of freedom, where the mobile platform and the base are connected by six legs, is shown in Fig. 7 d). The desired location of the mobile platform can be achieved by changing the length of the legs using controlled prismatic joints. This architecture was used by Gough in 1947 to design tire testing machines and inspired the design of a flight simulator (Fig. 7 e). It is known as Gough-Stewart parallel robot. Parallel link robots also called Delta robots consist of parallel links connected to a common base. Delta robots are used in pick-and-place systems [1-9].

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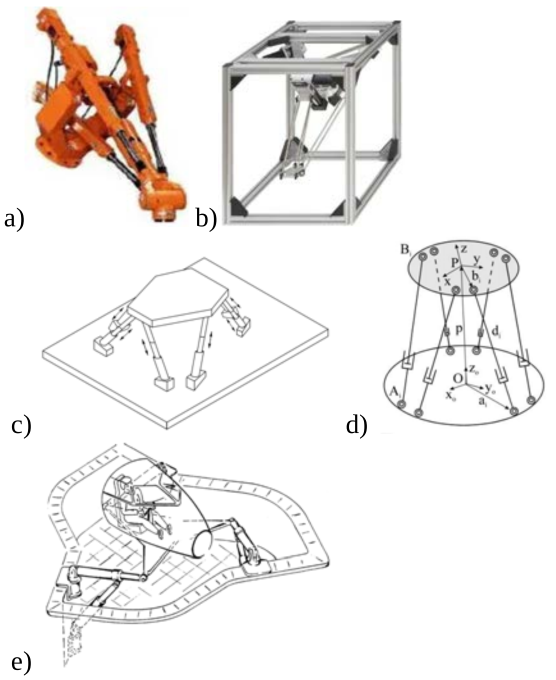

Figure 7 Parallel structure of robots a) Woux - ABB IRB940 Tricept Parallel Robot [6-7], b) Delta robot with number of axes 3, c) scheme of parallel robot [7],d) kinematic scheme of parallel robot [9], e) the design of a flight simulator

4 Kinematic analysis of mechanisms

Today's requirement is to design mechanisms that meet various technological and functional requirements for their operation in the production process. This also applies to the demands for the development of mechanical structures of manipulators and robots. Finding the position of the end member of the kinematic chain of the manipulator of the individual members of the industrial robot based on the known angular rotations in the individual kinematic pairs is a relatively simple task of solving direct kinematics. More demanding is the inverse task of kinematics, where the position and orientation of the gripper are given, and we are looking for the angular coordinates of individual kinematic pairs [4-6]. We encounter the solution of these two tasks most often in the kinematic analysis of robots and manipulators.

In the two-member robotic arm in Fig. 8 with rotational kinematic pairs in individual joints, with arm rotation angles θ_1 and θ_2, we will encounter the solution of the direct and inverse kinematics problem.

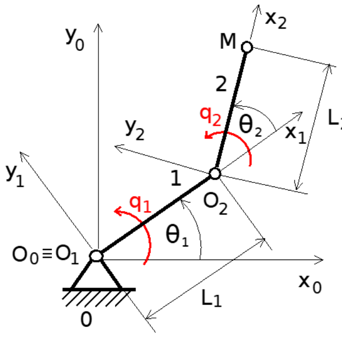

Figure 8 Two-link manipulator kinematic scheme

When solving a direct kinematic problem, the kinematic equations (1) and (2) determine the position of the end point of the arms M.

$$x_M = L_1 cos\theta_1 + L_2 cos(\theta_1 + \theta_2) \quad (1)$$
$$y_M = L_1 sin\theta_1 + L_2 sin(\theta_1 + \theta_2) \quad (2)$$

With the known sizes of the angular quantities θ_1 and θ_2, we can determine the position of the point M described by the coordinates x_M and y_M and solve the direct problem of kinematics. With the known position of point M with coordinates x_M and y_M, we can determine the angles θ_1 and θ_2. We solve the inverse problem of kinematics [10-13].

4.1 The forward kinematics

The forward kinematics equation establishes a functional relationship between the joint variables and the position and orientation of the end effector. The inverse kinematics problem consists of determining the joint variables corresponding to the given position and orientation of the end effector. The solution of this problem is of fundamental importance for the transformation of the movement specifications assigned to the end effector in the operative space, to the corresponding movements of the joint space, which enable the execution of the desired movement. Regarding the direct kinematic equation (1) and (2) the end-effector position are calculated in a unique way once the joint variables L_1 , L_2 , θ_1 and θ_2 are known.

In the two-member robotic arm in Fig. 8 with rotational kinematic pairs in individual joints, with arm rotation angles θ_1 and θ_2, when solving a direct kinematic problem, kinematic equations (1) and (2) determine the position of the end point of the arms M. This is the solution of a direct kinematic problem.

4.2 The workspace of robot

The workspace of an industrial robot can be defined as a set of all end positions of the end of the arm, i.e. flanges that can be reached at the end positions of each of the robot's axes. It is determined by the volume of space within the maximum reach of the robot flange or effector, which is attached to the robot flange (gripper, tool, etc.).

The workspace is an important parameter when planning a robot task. All his movements must remain

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inside the workspace as shown in Fig. 11 a). It is considered one of the most important characteristics for choosing a suitable robot.

An arbitrary orientation of the end effector is usually not possible in the border positions of the robot workspace. As a rule, it is difficult for the effector to access the manipulated object, which is in location a borderline position of the workspace.

The choice of the workspace depends on the nature of the work tasks, which depend on the used kinematic structure of the robot. Structures with serial kinematics are characterized by the fact that they perform movement independently of each other. The resulting movement is composed of a certain sequence of movements performed by these kinematic pairs.

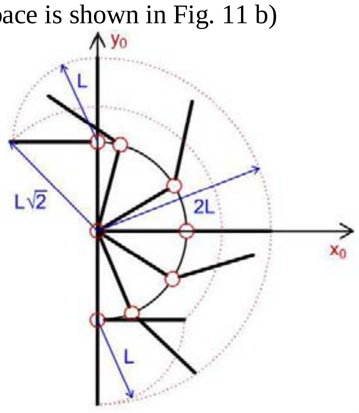
The working space of the manipulator is a subspace of the entire possible space of all arm positions that the end point of the manipulator's gripper can take. The size and shape of the working space of the manipulator depends on the properties of the manipulator, namely on the geometric dimensions of the arms L_1 and L_2 and on the limitations of the joint variables q_1 and q_2. The joint variables in our case are $q_1 = \theta_1$ and $q_2 = \theta_2$.

The following graph (Fig. 11 b) shows all the x,y data points generated by cycling through various combinations of angles θ_1 (theta1) and θ_2 (theta2) and the derivation of the x and y coordinates for the endpoints of the arms. This space can be rendered using the commands shown in Fig. 10 [10-13].

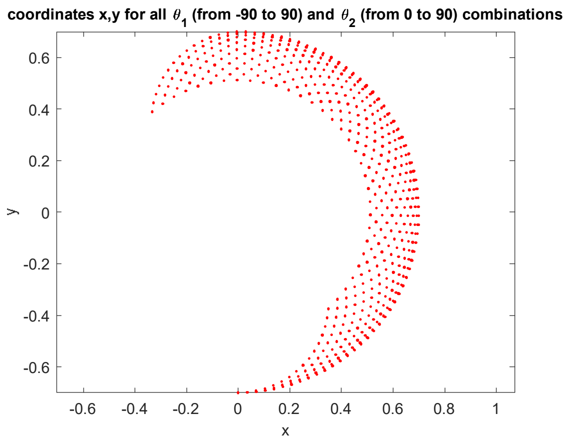
```
figure(2)
L1 = 0.35; % length L1 of first arm
L2 = 0.35; % length L2 of second arm
theta1 = -pi/2:0.1:pi/2; % all possible theta1 values
theta2 = 0:0.1:pi/2; % all possible theta2 values
[THETA1,THETA2] = meshgrid(theta1,theta2); % generate a grid of theta1 and theta2 values
X = L1 * cos(THETA1) + L2 * cos(THETA1 + THETA2); % x coordinates
Y = L1 * sin(THETA1) + L2 * sin(THETA1 + THETA2); % y coordinates
data1 = [X(:) Y(:) THETA1(:)]; % create x y theta1
data2 = [X(:) Y(:) THETA2(:)]; % create x y theta2
plot(X(:),Y(:),'r.','LineWidth',2);
axis equal;
xlabel('x','fontsize',10)
ylabel('y','fontsize',10)
title('coordinates x,y for all \theta_1 (from -90 to 90),\theta_2 (from 0 to
90)','fontsize',10)
text(-0.4,-0.35,'M_0 (x,y) = (0.4,-0.4)'),...
text(-0.4,0.4,'M_{tf} (x,y) = (0,0.6)')
grid on
```

Figure 10 M-file in Matlab m-file in Matlab for determining the workspace of two-link manipulator

The workspace is shown in Fig. 11 b)



a)



b)

Figure 11 Workspace a) two link arms with workspace, b) the workspace of two link arms for the given joint limits of angles θ_{10}=-90°, θ_{20}=0°, θ_{1tf}=90°, θ_{2tf}=90° in Matlab

Workspace with joint restrictions:
$0^{\circ} \leq \theta_1 \leq 180^{\circ}$ and $-90^{\circ} \leq \theta_2 \leq 270^{\circ}$ is shown in Fig. 12.

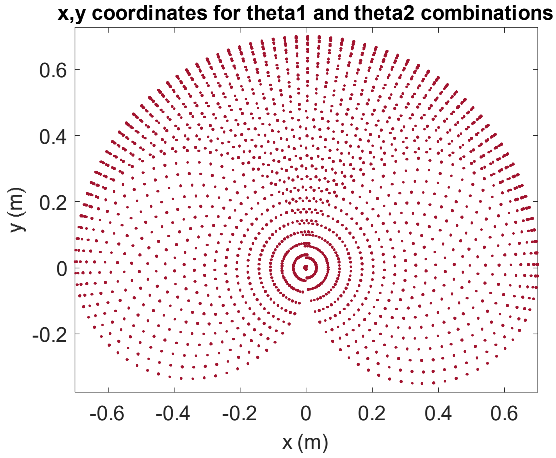


Figure 12 Two-link manipulator workspace with angles in joints $0^{\circ} \leq \theta_1 \leq 180^{\circ}$ and $-90^{\circ} \leq \theta_2 \leq 270^{\circ}$

With the restrictions for θ_1 and θ_2 the workspace will be in the form shown in Tab. 1.

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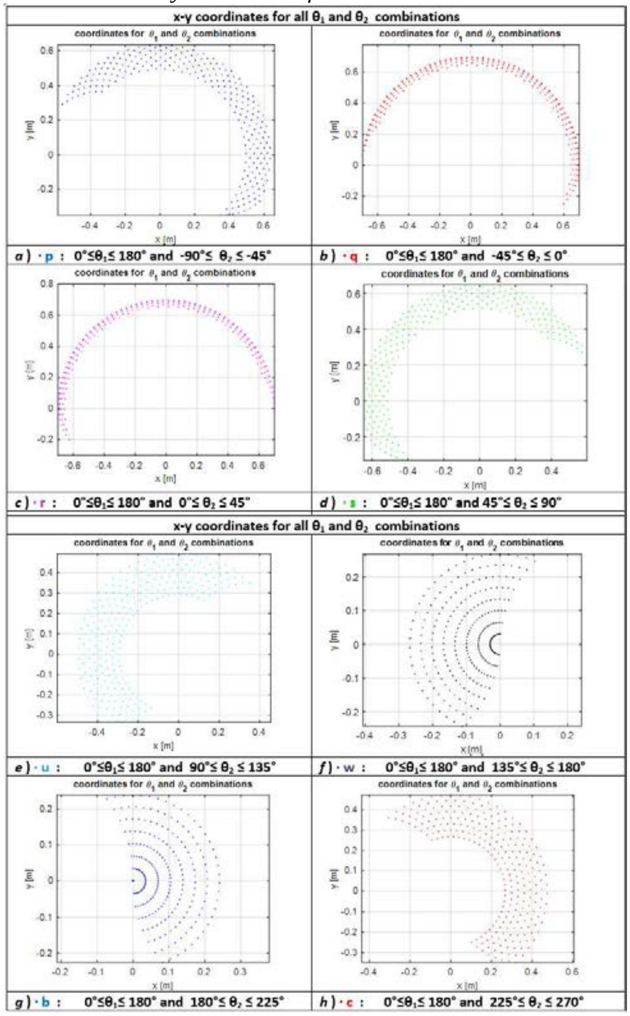
Table 1 The x-y coordinates for all θ_1 and θ_2 combinations



The resulting workspace with joint constraints is shown in Fig. 13.

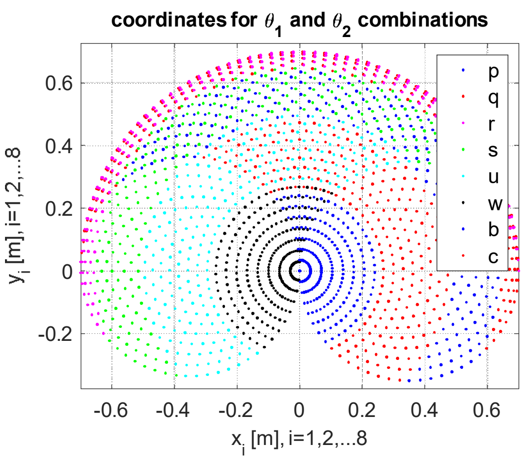


Figure 13 Two-link manipulator – the position of the endpoint

Angles θ_1 and θ_2 of the arms of length L_1 and L_2, at the initial position of the arms and the final position of the arms in Fig. 14 are determined using the m-file in Fig. 16 a).

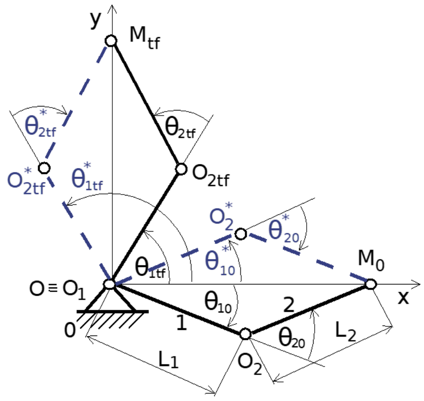


Figure 14 Two link arms in the given joint limits θ_{10}=-90°, θ_{20}=0°, θ_{1tf}=90°, θ_{2tf}=90°

The trajectory of the end point M when moving from position M_0 to position M_{tf} is shown in Fig. 14. The m-file for determining the trajectory when moving from point M_0 to point M_{tf} is in Fig. 16 b) [10-13].

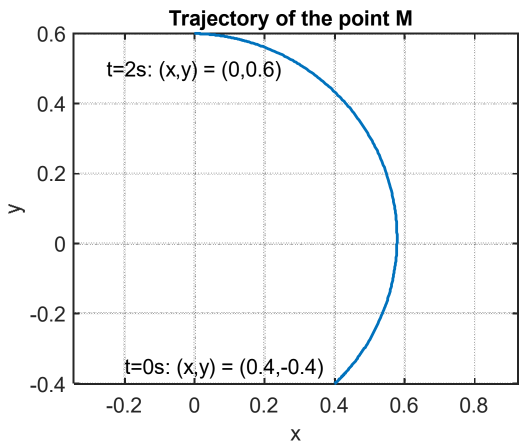


Figure 15 Trajectory of the two-link manipulator from position M_0 (0.4, -0.4) to the position M_{tf} (0, 0.6)

a)

```
clc
L1=0.35
L2=0.35
xM0=0.4
yM0=-0.4
xMtf=0.0
yMtf=0.6
syms theta10 theta20 theta1tf theta2tf
E10 = L1*cos(theta10)+L2*cos(theta10+theta20)-xM0;
E20 = L1*sin(theta10)+L2*sin(theta10+theta20)-yM0;
[theta10, theta20] = solve(E10,E20);
theta10 = double(theta10*(180/pi))
theta20 = double(theta20*(180/pi))

E1tf = L1*cos(theta1tf)+L2*cos(theta1tf+theta2tf)-xMtf;
E2tf = L1*sin(theta1tf)+L2*sin(theta1tf+theta2tf)-yMtf;
[theta1tf, theta2tf] = solve(E1tf,E2tf);
theta1tf = double(theta1tf*(180/pi))
theta2tf = double(theta2tf*(180/pi))
```

b)

```
% Trajectory
% angles for t=0 and t=tf
tf = 2;
theta10 = -9*pi/180;
theta20 = -72*pi/180;
theta1tf = 121*pi/180;
theta2tf = -62*pi/180;
% Equations for a coefficients
T = [ tf^5 tf^4 tf^3
5*tf^4 4*tf^3 3*tf^2
20*tf^3 12*tf^2 6*tf ];
c = [ theta1tf-theta10; 0; 0 ];
disp('Koeficienty pri uhle zamena theta1:')
a = T\c
% Equations for b coefficients
d = [ theta2tf-theta20; 0; 0 ];
disp('Koeficienty pri uhle zamena theta2:')
    b= T\d
% Position of point M: x_M=x , y_M=y
L1 = 0.35;
L2 = 0.35;
t = linspace(0,2,401);
tq = [ t.^5; t.^4; t.^3 ];
theta1 = theta10 + a'*tq;
theta2 = theta20 + b'*tq;
x = L1*cos(theta1) + L2*cos(theta1 + theta2);
y = L1*sin(theta1) + L2*sin(theta1 + theta2);
% Plot path of point M
plot(x,y),...
xlabel('x'),...
ylabel('y'),...
axis equal
title('Trajectory of the point M '),...
text(0.5,-0.35,'t=0s: (x,y) = (0.4,-0.4)'),...
text(-0.1,0.5,'t=2s: (x,y) = (0,0.6)')
grid on
```

Figure 16 a)M-file for θ_1 and θ_2 , b) *M-file for trajectory of two-link manipulator*

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The trajectory of the end point M when moving from position M_0 to position M_{tf} (Fig. 15) is in the workspace in Fig. 17 for angular size restrictions:

$$-90^{\circ} \leq \theta_1 \leq 90^{\circ} \text{ a } 0^{\circ} \leq \theta_2 \leq 90^{\circ}.$$

The trajectory in Fig. 17 will be drawn by completing the commands:

```
plot(X(:),Y(:),'r.',x,y,'b-','LineWidth',2),
text(-0.4,-0.35,'M_0 (x,y) = (0.4,-0.4)'),
text(-0.4,0.4,'M_{tf} (x,y) = (0,0.6)')
```

to the above-mentioned m-file for determining the workspace in Fig. 10.

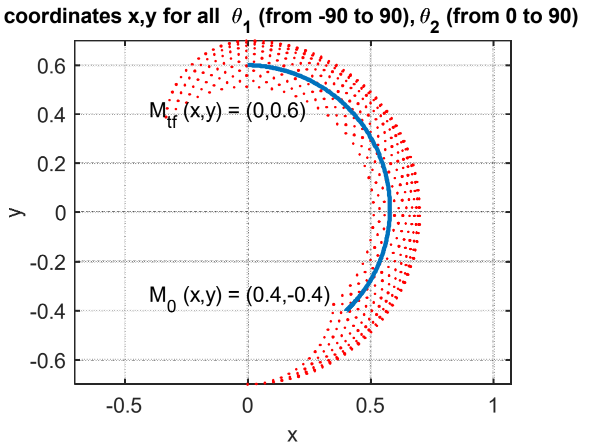

Figure 17 Two link arms and the workspace of the 2R robot for the given joint limits θ_{10}=-90°, θ_{20}=0°, θ_{1tf}=90°, θ_{2tf}=90° in Matlab with trajectory from point M_0 to point M_{tf}.

Various objects, obstacles, tools, etc. can be placed in the robot's handling space. Their position can be easily described with respect to the base space. The forward kinematics is used to determine the relative position of the arm with respect to the objects located in the manipulation space of the robot [6-9].

5 Conclusion

The paper deals with the issue of kinematic analysis of an industrial robot. The kinematic structure of the robot is represented by an open kinematic chain. A direct kinematics problem was used to solve the problem. The solution procedure consists of the calculation and graphical representation of the manipulation space of the end effector while considering various joint constraints. The analysis also includes a graphical representation of the end effector trajectories.

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References

[1] ANGELES, J.: *Fundamentals of Robotic, Mechanical systems*, 2nd ed., Springer Verlag, New York, USA, 2003.
[2] SPONG, M.V.: *Fundamentals of Robotic, Mechanical systems, 2nd* ed., Springer, 2002.
[3] MURRAY, J.C.: *A mathematical introduction to robotic manipulation*, CRC Press, Boca Raton, FL, 1994.
[4] LATOMBE, J.C.: *Robot Motion Planning*, Kluwer Academic Publishers, Boston, 1991.
[5] CRAIG, M.V.: *Fundamentals of Robotic, Mechanical systems*, 2nd ed., Springer, 2002.
[6] SCIAVICCO, L., SICILIANO, B.: *Modelling and Control of Robot Manipulators*, 2nd ed., Springer-Verlag, London, 2000.
[7] DUYSINX, P., GERADIN, M.: *An introduction to Robotics: Mechanical Aspects*, University of Liège, Liège, 2004.
[8] CRAIG, J.: *Introduction to Robotics: Mechanics and Control*, Pearson Prentice Hall, 3rd ed., 2005.
[9] CECCARELLI, M., OTTAVIANO, E.: *Kinematic design of Manipulators*, University of Cassino, Italy, 2008.
[10] HRONCOVÁ, D., RÁKAY, R., LIPTÁK, T.: Sim Mechanics and Forward and Inverse Problem of Dynamics, *Journal of Automation and Control*, Vol. 3, No. 3, pp. 58-61, 2015.
[11] HRONCOVÁ, D., DELYOVÁ, I., FRANKOVSKÝ, P.: Kinematics of Positioning Device for Material Handling in Manufacturing, *Acta logistica*, Vol. 8, No. 1, pp. 11-18, 2021. https://doi.org/10.22306/al.v8i1.194
[12] HRONCOVÁ, D., SINČÁK, P. J., MERVA, T., MYKHAILYSHYN, R.: Robot trajectory planning, *MM Science Journal*, Vol. 2022, No. November, pp. 6098-6108, 2022. https://doi.org/10.17973/MMSJ.2022_11_2022093
[13] HRONCOVÁ, D., MIKOVÁ, Ľ., VIRGALA, I., PRADA, E.: Kinematics of Two Link Manipulator in Matlab/Simulink and MSC Adams/View Software, *MM Science Journal*, Vol. 2021, No. October, pp. 4749-4756, 2021.
[14] Factory Automation | Gantry Robots, Rack and Pinion Gantry Robots, Track Motion Automation Systems, Components, [Online], Available: https://www.uskoreahotlink.com/products/factory-automation/gantry-robots-rack-and-pinion [07 Jan 2023], 2023.

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