TWO-LEGGED ROBOT CONCEPTS

LUKAS LESTACH[1], MICHAL KELEMEN[1], TATIANA KELEMENOVA[1], IVAN VIRGALA[1], LUBICA MIKOVA[1], ERIK PRADA[1], DARINA HRONCOVA[1], MARTIN VARGA[1], PETER JAN SINCAK[1], TOMAS MERVA[1],

[1]Technical University of Kosice, Faculty of Mechanical Engineering, Kosice, Slovakia

DOI: 10.17973/MMSJ.2022_10_2022091

michal.kelemen@tuke.sk

The article deals with the concepts of a two-legged walking robot. Three kinematics concepts are proposed in order to achieve the lowest possible number of actuators and the best possible energy efficiency. Walking cycle algorithms are also proposed. These concepts have been assessed and evaluated in several respects in order to select the optimal kinematic concept.

KEYWORDS

Gripper, robot, actuator, kinematics, simulation

1 INTRODUCTION

Two-legged robots represent a movement concept that allows you to overcome terrain with different obstacles and different types of terrain surface. In general, two approaches are possible: a human-like concept and an anthropomorphic concept that has a different kinematics than a human. When designing a robot, the goal is always to build a concept that will have energy efficient movement at the lowest possible weight. The key problem with two-legged concepts is their stability, which is a relatively complicated problem that becomes even more complicated at higher walking speeds [Chen 2021, Sobirin 2021, Virgala 2020b, Fevre 2019, Gao 2021, Virgala 2022].

Inspired by current designs of two-legged walking chassis and with the help of their own ideas, three robot concepts were created, which differ in kinematic arrangement, type and number of actuators used. However, they have in common a chassis structure assembled as a two-legged single-axle, ie the legs of the robot are arranged in parallel. This means that the hip joints are located on the platform next to each other and have a common axis of rotation. This axis is oriented perpendicular to the direction of movement. All three variants use a very similar way of walking, in which the feet are crossed. With this solution, it is possible to circumvent the need to transfer the centre of gravity from one foot to the other by tilting the robot and thus the platform from side to side. Such tilts can adversely affect the functionality of the manipulator or the recording quality of the sensing devices located on the robot platform. During the locomotion of variants, at least one of the legs is always in contact with the surface and at the same time it is in the centre of gravity and there is no so-called phase of flight in which both feet are above the surface. In addition, the platforms of all variants maintain a constant height above the floor when walking and can also adjust this height if necessary.

Based on the kinematic schemes of individual variants, corresponding models were created in the Solidworks program, on which the walking of concepts was simulated and the criteria for comparison were evaluated. The walk of variants is also shown in this paper in the relevant figures and with a description of the main parts of their concepts.

During the simulations of the walking variants, slight fluctuations of the platforms were recorded due to the dynamic influences of the actuators. These effects caused the entire robot structure to vibrate. It is possible to reduce them on real models by controlling the acceleration of action members in the activity.

2 DESIGNED CONCEPTS OF ROBOT KINEMATICS

2.1 Biped robot concept A

This concept (Figure 1) has six degrees of freedom. Each leg of the robot has three planar joints, one in the lumbar, knee and ankle joints. All of them are equipped with rotary actuators. It contains the base, upper and lower parts of the legs and feet, between which there are individual rotating joints. Walking algorithm of this concept is shown on Figure 2.

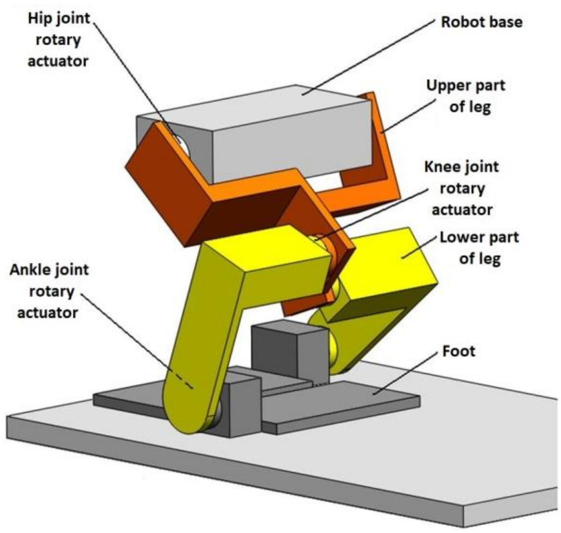

Figure 1. Biped robot concept A

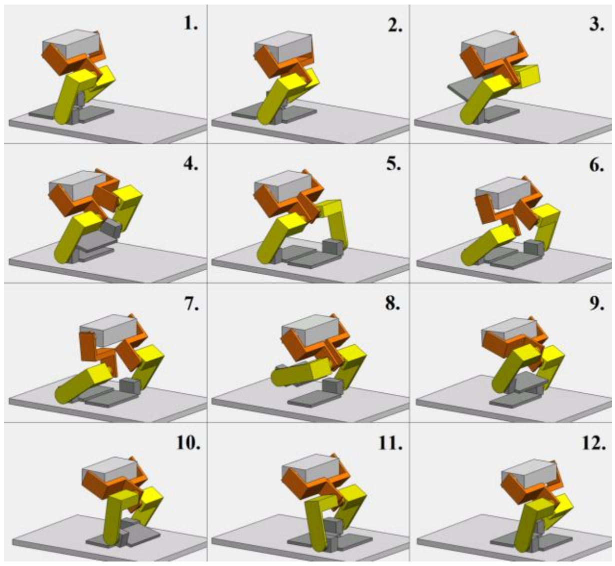

Figure 2. Walking algorithm of biped concept A

The individual phases of walking are shown in Fig. 2. The movement starts in position 1 by gradually moving the base forward to point 2 and thus also by moving the centre of gravity to the right foot. This movement is realized by the simultaneous movement of all six rotary actuators. Subsequently, the left foot is lifted, then moved in front of the right foot and placed on the floor at point 5. During this position, the motor in the ankle joint must ensure that the foot is parallel to the floor. At this point, the centre of gravity of the robot is still in the right foot zone, which means that the platform moves forward to point 7. From this point, the whole cycle is repeated by performing the second step with the right foot.

2.2 Biped robot concept B

This variant (Figure 3) also has six degrees of freedom, but does not use six planar joints, but only four. The other two degrees of freedom are represented by linear guides that replace the knee joints. The planar joints are driven by rotary motors and linear actuators are used to drive the linear guides. Walking algorithm of this concept is shown on Figure 4.

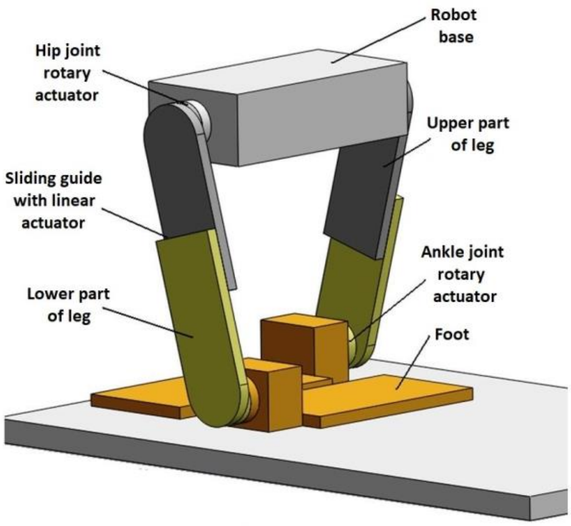

Figure 3. Biped robot concept B

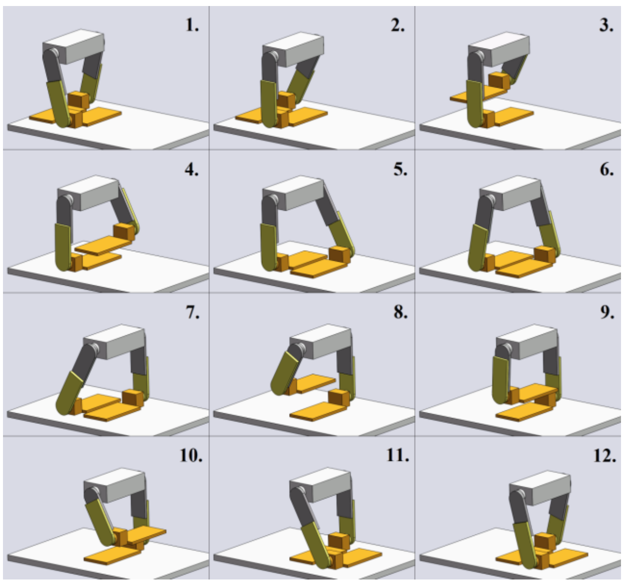

Figure 4. Walking algorithm of biped concept B

The locomotion algorithm of concept B starts by moving the platform from the basic position to point 2, i.e. by moving the centre of gravity to the zone of the right foot. During this movement, all action members of the concept move simultaneously. Furthermore, the linear motor of the left foot is inserted, i.e. the stroke of the left foot. The lift must be sufficient to prevent the feet from coming into contact when the left foot is subsequently moved forward to point 4 by means of a rotary motor in the hip. This contact could result in a loss of stability and a consequent collapse of the concept. At point 5, the left foot is stepped on the floor by extending the linear motor of the left foot. When stepping on it, it is necessary to increase the stability so that the foot rests on the floor over the entire surface. For this, the parallelism of the foot and the floor must be ensured, which is ensured by a rotary motor in the ankle joint. By simultaneous movement of the drives, the platform moves forward to the basic position at point 6, where the weight is evenly distributed between the two legs. From this point until point 12, the locomotion cycle is repeated in the right foot step.

2.3 Biped robot concept C

Concept C (Figure 5) has four degrees of freedom. These are formed at each foot by a linear guide and a parallelogram mechanism with one degree of freedom. It has the function of guaranteeing the parallelism of the feet with the robot platform. This mechanism consists of four planar joints and two equally long parallel rockers. It is driven by one rotating actuator located in the foot. The placement in the foot is suitable to reduce the centre of gravity and thus increase the stability of the robot. A linear actuator is provided as the drive of the sliding guide, which positions the height of the parallelogram.

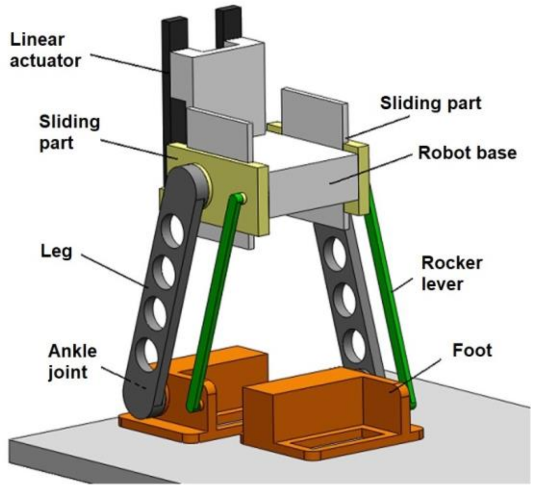

Figure 5. Designed leg and rocker lever of the robot

The movement of concept C to point 2 is realized by the simultaneous movement of all four action members. During this movement, the base is moved forward so that the centre of gravity is transferred to the floor plan of the left foot. After transferring the weight of the robot to the left foot, the right foot can be lifted together with the entire parallelogram mechanism by inserting the linear drive of the right foot. When the right foot is sufficiently raised at point 3, the rotation of the motor in the right ankle joint begins to move the foot forward by means of a kinematic mechanism to point 5. This mechanism also ensures that the foot is parallel to the floor when stepped on at point 6, which is only by sliding the right foot linear motor. Subsequent movement of the base forward and thus moving the centre of gravity over the right foot, the cycle is repeated by the step of the left leg of the robot. The whole course of walking is shown in Figure 6.

The application of linear drives introduced the possibility of compensating vertical movements caused by rotary drives into this concept. The compensatory movement of the linear drives can thus stabilize the base of the robot. The application of linear actuators has made this concept a non-anthropomorphic concept that differs significantly from the kinematics of human walking.

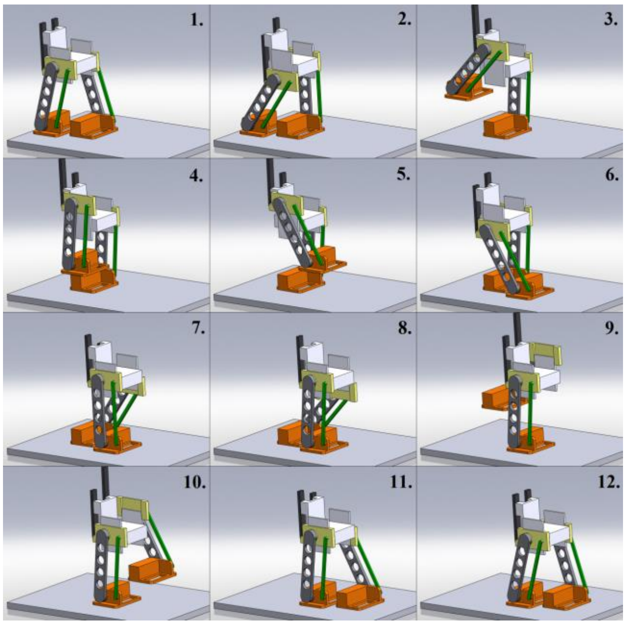

Figure 6. Walking algorithm of biped concept C

3 EVALUATION OF BIPEDAL ROBOT CONCEPTS

The most important criteria were selected for the evaluation of robot concepts:

- K1 – Energy efficiency
- K2 – Self-locking base position
- K3 – Number of degrees of freedom
- K4 – Control complication
- K5 – Ability to overcome obstacles
- K6 – Load capacity
- K7 – Price

All of these criteria (Figure 7) were compared in terms of importance, and those criteria that were more important in pairwise comparisons are highlighted and scored. The criterion that received the most points is the most important. The criterion that received the lowest number of points is the least important.

Pairwise comparison					
K1 K2	K1 K3	K1 K4	K1 K5	K1 K6	K1 K7
	K2 K3	K2 K4	K2 K5	K2 K6	K2 K7
		K3 K4	K3 K5	K3 K6	K3 K7
			K4 K5	K4 K6	K4 K7
				K5 K6	K5 K7
					K6 K7

Criterion	Score	Order
K1	1	6
K2	6	1
K3	3.5	3
K4	1.5	5
K5	5	2
K6	1	6
K7	3	4

Criterion	K1	K2	K3	K4	K5	K6	K7
Importance coefficient	1	2	1.5	1.1	1.8	1	1.4

Figure 7. Pairwise comparison and identification of criterion importance; Assigning a coefficient of importance

In the assessed concepts, we will consider specific types of actuators, which were selected earlier on the basis of preliminary calculations.

3.1 *Criterion K1 – Energy efficiency*

To evaluate this criterion, the display of the results of the current energy consumption via the Power Consuption item was switched on during the motion simulation in SolidWorks. The results of individual action members were transferred to Excel using the Export to spreadsheet link, where the consumption of action members of individual concepts was added up. Thus, the following two-step energy acquisition sequences were obtained.

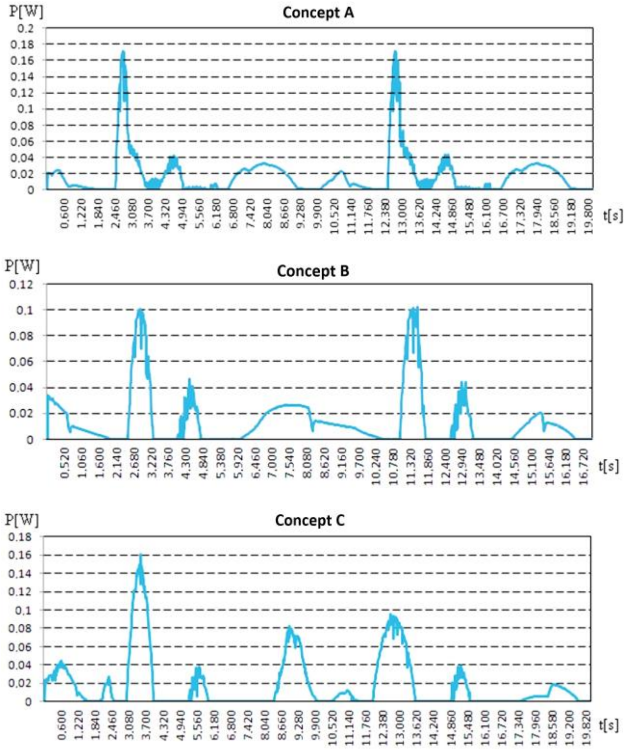

Figure 8. Graphs of energy consumption of individual concepts

Since the calculation was performed at 50 FPS sampling, i.e. every 0.02 s, the resulting consumption represents a multiple of this time with the sum of all instantaneous sampling values obtained in Excel. The formula for calculating consumption is:

$$W = \sum_{i=0}^{n} P_i \times t \; [Ws] \quad (1)$$

(1)

After substituting into this formula (1), the consumptions of the concepts are as follows:

W_A = 0.358 Ws; W_B = 0.235 Ws; W_C = 0.351 Ws.

The scoring of concepts results from the selected conditions:

- 1 point if W > 300 Ws
- 2 points and 200 Ws < W <300 Ws
- 3 points and W < 200 Ws

The consumptions obtained are only theoretical and do not take into account the effectiveness of individual actuators. To find more accurate values, it is necessary to perform measurements on real actuators.

3.2 *Criterion K2 – Self-locking base position*

The evaluation was performed in the SolidWorks program, assuming that the linear motor has the ability to self-lock even without power supply thanks to the screw mechanism, unlike the rotary servomotor. The self-locking value of the used linear motor was obtained from the manufacturer's documentation and has a value of 43 N. The concepts were exposed to gravity and the behaviour of their base was monitored.

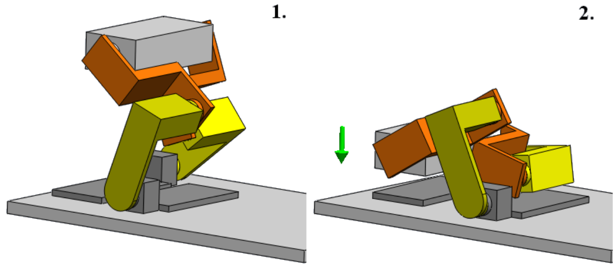

Figure 9. Behavior of concept A without power supply under gravity

Since concept A (Figure 9) uses only rotating actuators, gravity has caused the robot base to fall on the foot. This situation can only be avoided by constantly supplying the actuators. However, this would have an adverse effect on energy efficiency. Therefore, concept A is rated 1 point.
The robot concept B (Figure 10) uses a sliding guide with a linear actuator instead of a knee joint with a rotating member. This solution will ensure that the position of the base is maintained even without power supply. The maximum force load of the linear motor under gravity reached 1.4 N. Concept B gains 3 points with criterion K2.

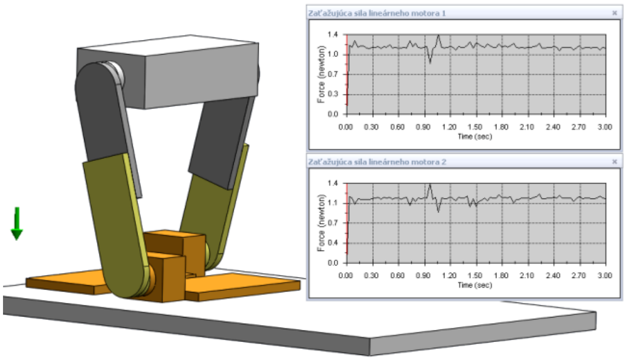

Figure 10. Stress and strain distribution - robot leg

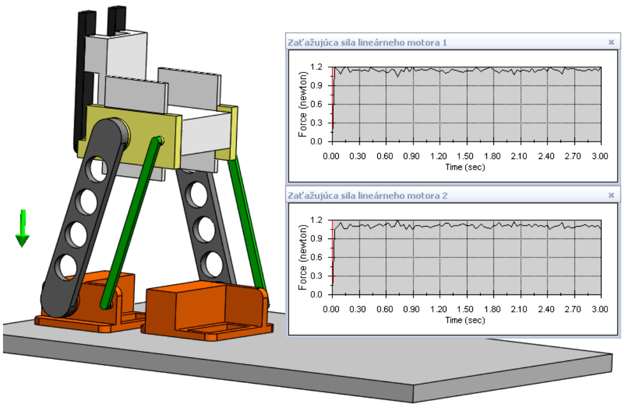

Figure 11. Influence of gravitational action on the behaviour of the robot concept C

Since concept C (Figure 11) does not have a rotary joint knee joint but instead a sliding guide, it has similar properties to concept B. The only difference is in the load force of the linear motor, which takes on a value of 1.2 N. Concept C thus gains 3 points, as well as concept B.

3.3 Criterion K3 – Number of degrees of freedom

In general, it is advantageous to use fewer degrees of freedom and thus fewer actuators while maintaining functional properties. The evaluation is based on the following conditions:

- 1 point if the number of degrees of freedom > 6
- 2 points if the number of degrees of freedom is from 5 to 6
- 3 points if number of degrees of freedom < 5

Concept C has 4 degrees of freedom and thus gains 2 points. Concept A and Concept B have 6 degrees of freedom and therefore gain 1 point.

3.4 Criterion K4 – Control complication

If it is necessary to change the distance of the foot from the robot base when walking, then the concept of robot A has the most complicated control, as it is necessary to change the rotation of all three rotary motors at the same time to change this distance. For robot concepts B and C, this movement is ensured by simply inserting or removing the linear actuator. In addition, the C robot concept ensures parallelism of the foot and the platform in all phases of walking thanks to the parallelogram mechanism. In Concept A and Concept B, this parallelism must be ensured by the simultaneous control of the hip and ankle joint actuators. In view of these facts, the concept of robot A receives 1 point, the concept of robot B 2 points and the concept of robot C 3 points.

3.5 Criterion K5 – Ability to overcome obstacles

All three robot concepts use a similar walking principle, in which the feet cross each other. This makes it possible to circumvent the need to transfer the centre of gravity by tilting the base of the robot from side to side. They differ only in the arrangement and type of actuators used. The ability to overcome obstacles is therefore almost identical for all concepts. Therefore, the evaluation is the same and each robot concept gets 2 points.

3.6 Criterion K6 – Load capacity

The load capacity of all robot concepts was determined by gradually adding a loading force to the robot base, until the maximum load of one of the actuators was reached. For a linear motor, this is a force of 24.5 N, which was determined by experimental measurements. For a rotary engine, the limit torque is 9.6 kg.cm, after adjusting the units to 942 Nmm. The drive load profile was displayed in a simulation using Applied Force and Applied Torque items in SolidWorks.
From the graphs for the concept of robot A (Figure 12), it can be seen that the limit load of 942 Nmm occurred on a rotary motor in the knee joint at an applied force of 16 N. This force represents a weight of 1.63 kg placed on the platform. Under this load, the maximum torque on the rotary engine in the ankle joint was 420 Nmm and 705 Nmm in the lumbar joint.

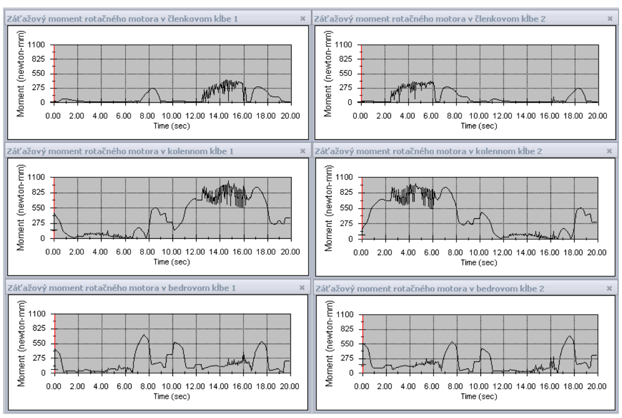

Figure 12. Load of actuators for the concept of robot A at a loading force of 16 N

The maximum permissible load in the robot concept B (Figure 13) occurred on a linear motor with a force of 20.5 N, i.e. 2.09 kg. The highest torque for rotary drives was 720 Nmm in the lumbar joint and 170 Nmm in the ankle joint.
The concept of the robot C was able to walk up to a load of 20 N, which was subject to the limit force of 24.5 N on a linear motor. The load capacity of the platform thus corresponds to a weight of 2.04 kg. At this weight, the rotating actuator located on the robot's foot was loaded with a torque of 690 Nmm.
The conditions for scoring are as follows:
- 1 point if load capacity < 1 kg
- 2 points if the load capacity is 1 to 2 kg
- 3 points if load capacity > 2 kg

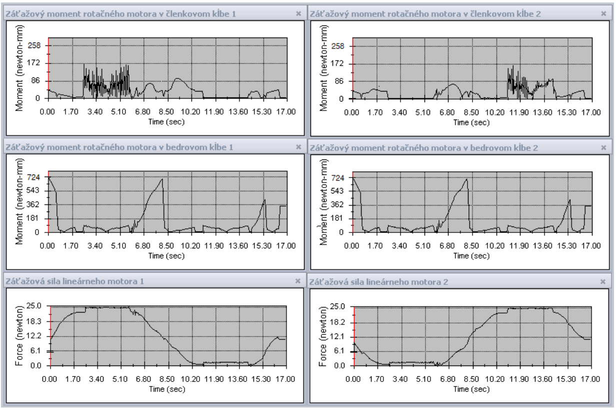

Figure 13. Load of actuators for the concept of robot B at a loading force of 20.5 N

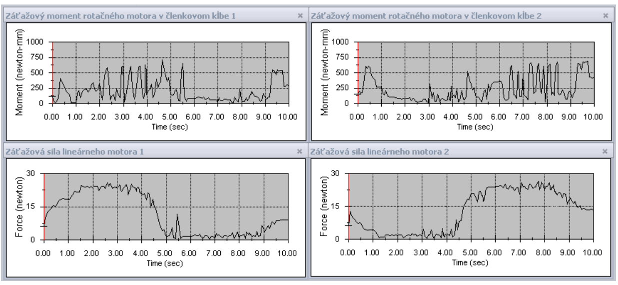

Figure 14. Load of actuators for the concept of robot C at a loading force of 20 N

3.7 *Criterion K7 – Price*

As all three robot concepts require a control unit, sensors, and batteries for their operation and are approximately as structurally demanding, the main difference in price is caused by the actuators used. The price of these special members was obtained from online stores and is € 114 for a linear motor and € 36 for a rotary motor. After recalculating and taking into account only the prices of the share members, the costs of concept A are € 216, the costs of concept B are € 372 and the costs of concept C are € 300. The evaluation for criterion K7 is given by the conditions:
by 1 point and price > 350 €
by 2 points if the price is 250 to 350 €
by 3 points and price < 250 €

4 FINAL EVALUATION OF ROBOT CONCEPTS

The obtained point evaluations of robot concepts are entered into a Table 1, where they are subsequently influenced by the weight of individual criteria. The sum of the adjusted points is the overall rating, which determines the order and the resulting design concept of the two-legged robot. In this evaluation, it is variant C.

Table 1. Overall evaluation of robot concepts

Criterion	K1	K2	K3	K4	K5	K6	K7	
Criterion weight	**1**	**2**	**1.5**	**1.1**	**1.8**	**1**	**1.4**	**Sum**
Concept A	1	1	1	1	2	2	3	15.4
Concept B	2	3	1	2	2	3	1	19.7
Concept C	1	3	2	3	2	3	2	22.7

5 PROPOSAL FOR FURTHER DEVELOPMENT OF THE ROBOT

After the evaluation, the final design of the concept became the concept of the robot C (Figure 15). The ability of concept C to overcome obstacles was verified by simulation (Figure 15). The possibilities of its further development are very wide and practically unlimited and depend on its further use. Examples of future concept development are given in the following points:
• Complement the concept with obstacle sensors that would make it possible to avoid objects and thus ensure movement in an unfamiliar environment. Infrared or ultrasonic sensors, for example, can be used as obstacle sensors.
• Equip the robot with the necessary sensors and a suitable motor control algorithm to overcome height obstacles.
• Equip the robot with a handling superstructure for gripping objects.

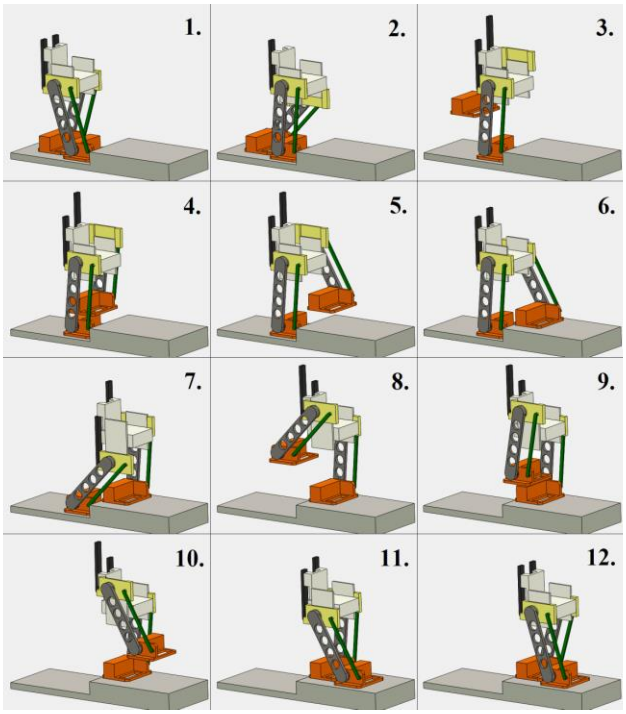

Figure 15. Stair climb simulation for robot concept C.

• Since the concept of the robot was created only for moving forward or backward, it is appropriate to supplement it with a concept designed for turning sideways (Figure 16).
• Another option is to use an accelerometer, which can be used to determine the current speed of the robot, but mainly to record its trajectory and determine its position in the environment.
• Using a gyroscope, it would be possible to control the tilt of the robot base while walking and, in the case of walking on a sloping surface, to obtain the data needed to correct the position of the centre of gravity to maintain stability.

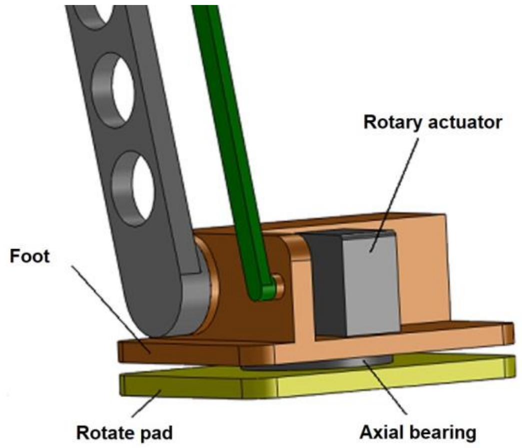

Figure 16. The concept of foot for turning the robot sideways

6 CONCLUSIONS

Three concepts of a two-legged robot solution using a similar walking principle were proposed, from which concept C was selected after evaluating the selected criteria. as few action members as possible. Other advantages include the ability to maintain a constant height of the robot base while walking or even the possibility of its necessary adjustment in any phase of the step by simple simultaneous insertion or withdrawal of linear drives. However, during the simulations, robot vibrations caused by the dynamic effects of the actuators were detected. Therefore, it is necessary in the real model to pay attention to these influences and minimize them by managing the acceleration of individual action members. Other possibilities for the development of the concept have been outlined above, but it is preferable to equip the concept with obstacle sensors and thus ensure movement in an unfamiliar environment. Other possible extensions depend on the use of a walking robot.

In connection with the design of robots, it is necessary to solve other related problems with sensor equipment [Kelemen 2021, Kelemenova 2021, Panda 2016, Zidek 2018], control systems [Kelemen 2014, Sapietova 2018], handling equipment [Bezak 2014, Bozek 2016, Mikova 2014] and effectors [Trojanova 2021, Bulej 2018, Virgala 2012 and 2014, Semjon 2016], production design [Jakubowski 2014], drive systems [Bozek 2021a,b, Peterka 2020, Nikitin 2020], and other relevant systems. It is also necessary to address issues of energy balance and system efficiency [Hajduk 2009, Kelemen 2012, Liptak 2018, Ostertag 2014, Pavlasek 2018, Pastor 2021, Pivarciova 2018 and 2022, Saga 2020, Suder 2021, Virgala 2014 and 2020a]. The robots can use information and landmarks from environment for navigation and such information may be provided by QR Codes or Data Matrix Codes [Karrach 2020].

Future work will be focused on the elaboration of the C concept and the direct and inverse kinematics task will be solved, and it is also important to solve the stability of the robot's locomotion. The stabilization of the base of this robot provides space for the application of this concept as a means of transport for the transport of people, but for this application it will be necessary to solve an enlarged model of this robot.

ACKNOWLEDGMENTS

The authors would like to thank the Slovak Grant Agency - projects VEGA 1/0201/21 and VEGA 1/0436/22. This work was supported by the Research Platform focused on Industry 4.0 and Robotics in Ostrava Agglomeration project, project number CZ.02.1.01/0.0/0.0/17_049/0008425 within the Operational Program Research, Development, and Education.

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CONTACTS:

Michal Kelemen, Prof. Ing. PhD.
Technical University of Kosice, Faculty of Mechanical Engineering
Institute of Automation, Mechatronics, Robotics and Production Techniques
Letna 9, 04200 Kosice, Slovak Republic
michal.kelemen@tuke.sk