

THE ISSUE OF ENERGY MANAGEMENT IN WALKING MACHINES

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Abstract

The energy management is a serious issue in the platforms of mobile robots, and especially walking robots. The solutions are sought so as to obtain the furthest possible range with the energy resources at the disposal. Properly adjusted configuration of the drives and the manner of energy management has a key impact on effectiveness of the drives. The article presents the most important features of the basic driving systems, possible configurations, and steering manners along with the assessment of their effectiveness. The article will present classical and hybrid drives. The authors present a sample analysis of energy "costs" of steering for the selected systems. The analysis will be supported with results of the simulation performed with the use of constructed computer models.

The guidelines for designing of the systems for walking platforms will be proposed, enabling to obtain high dynamics and energy efficiency of the system.

Keywords: *drive of a walking machine, energy costs in a mobile machine, linear load-sensing systems*

1. Introduction

Robotics is the area of technique, which is experiencing its renaissance. It stems from many reasons. Both have economic and social meaning. Many areas of life open for utilisation of robots. Stationary robots used in the process of production perform repetitive actions. At present, robots are entering hospitals, agricultural and forestry holdings and constantly conquer new areas. Another field in which robots achieve spectacular successes are military applications.

Despite that, presently, the vast majority of the robots used are stationary devices; the importance of mobile robots in economy and security systems is increasing. One of the criteria of assessment of their ability to perform tasks is the range and ability to handle obstacles.

Due to the driving system, mobile robots may be divided into wheeled, track-laying, and walking robots. Each of them has their own advantages and drawbacks. Wheeled platforms have the ability to move quickly over the hardened surface, track laying can move on the soft ground and in some configurations of the tracks, they can climb the stairs and other terrain obstacles. The highest terrain capability belongs to the walking robots, which way of moving mimics that of the living creatures. The problem of the walking robots is configuration of the driving systems providing maintenance of balance and the most optimal use of energy resources.

At present, it is possible to distinguish robots with multiple pairs of legs, where the problem is finding the optimal algorithm of moving them. The second dynamically developing branch is humanoid robots – two-leg. In this case, the most prominent are the problems of maintaining balance and energy management. The cycle of mechanical energy transformations occurs in the human body (Fig. 1), which enables achieving exceptional energy effectiveness of the system. Advancement of science enables us more precisely mimic human movement in the walking machines.

Walking machines find application in places, where it is necessary to change configurations of the platform setting. It results with frequent change of potential and kinetic energy. The issue

of reclaiming and transforming of energy is far more complicated than in the wheeled and track-laying vehicles especially that we have to deal with linear drives of pivot points. Additionally, the change of the centre of gravity height imposes slowing down of the systems with the use of transformation of energy or application of the self-locking systems.

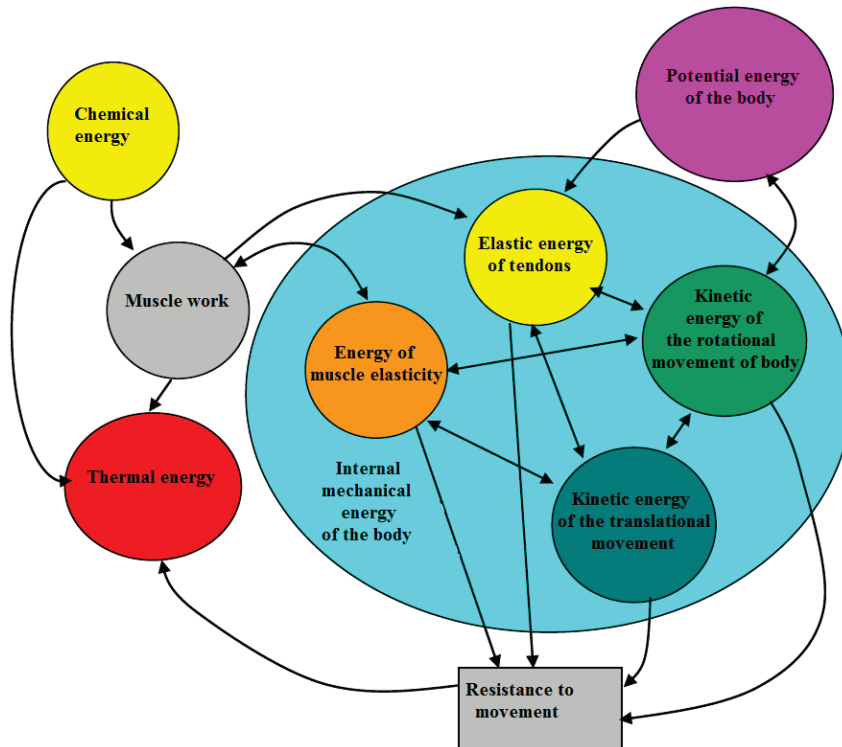


Fig. 1. Energy transformations in human movement

2. Drive of the walking robots

A separate problem in the mobile machines is the basic energy source, which enables the machine to travel large distances.

The majority of large walking machines utilises the hybrid drive in which the diesel engine powers the pump and electric generator. Further, the energy in the hydrostatic or electric form is transported to the execution units. In many cases, the energy storage cells are used, which lowers momentary load of the pump or the generator, and thus the fuel consumption. It allows reclaiming energy, especially in the electric drives.

For the relatively small group of applications it is possible to utilise rotary combustion engines and electric gear motors propelling the limbs via cam-crank mechanisms, like in Fig. 2.

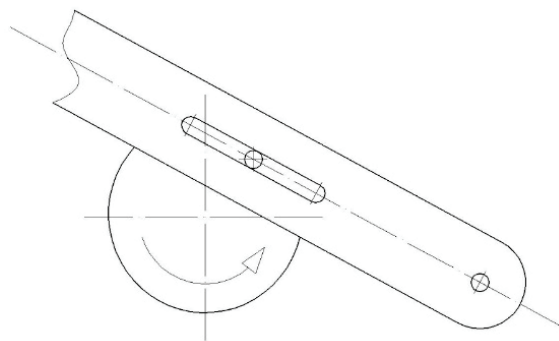


Fig. 2. Example of a cam-crank driving mechanism

Such machines comprise a large group of machines and devices moving over the flat not challenging terrain. They are useful only in the case of repetitive movements, namely when the robot performs steps with fixed length. When it is necessary the change the length of a step and the height of the tackled obstacle, it is necessary to apply more complicated driving systems.

At present, the so-called electric actuators are still larger and heavier than hydraulic cylinders, and when it is necessary to maintain one position for a longer period of time and transmit energy only from the engine to the powered point, construction of the driving system is often based on the screw self-locking drives, which significantly lowers the efficiency of the energy reclaiming system. For this reason, hydrostatic drives are still very attractive. We may note an advancement resulting from utilisation of new materials and technologies, despite having certain drawbacks.

As a result, despite existence of many drive systems for robots, it is still necessary to search for new solutions for drive systems allowing better use of energy. Development of modern materials provides possibilities of producing new gears, bands and couplers, which may imitate properties of muscles of humans and animals with their properties.

3. Energy properties of the fixed configuration systems

Inventing and improving the transistor manufacturing technology and application of the electric current control in the electromagnetic systems with the PWM method (Fig. 3) enables to draw only such amount of energy (impulse) from the energy source, which is necessary to perform a specific task. In this method, the effective current depends on filling of the voltage impulse, at the possibility of bi-directional current flow. There are losses of power in the transistor circuits, related to the voltage drops on the conductive transistor switches, diodes, and energy costs of control. Voltage drops on the semi-conductor switches are almost not dependant on the flowing current, losses of power are the product of the drawn current and voltage drop. Due to existence of induction in the circuits of the electric engines, there occurs the auto-transformation of voltage and current, so that:

$$U_{bat}Q_{bat} = U_{sil}Q_{sil} + \sum \Delta U_{TR}Q_{sil}, \quad (1)$$

where:

U_{bat} – voltage in the storage cell,

Q_{bat} – the impulse drawn from the storage cell,

U_{sil} – voltage on the motor terminals,

Q_{sil} – impulse that flowed through the motor,

$\sum \Delta U_{TR}$ – the total of voltage drops of the semiconductor switches controlling the direction of the current.

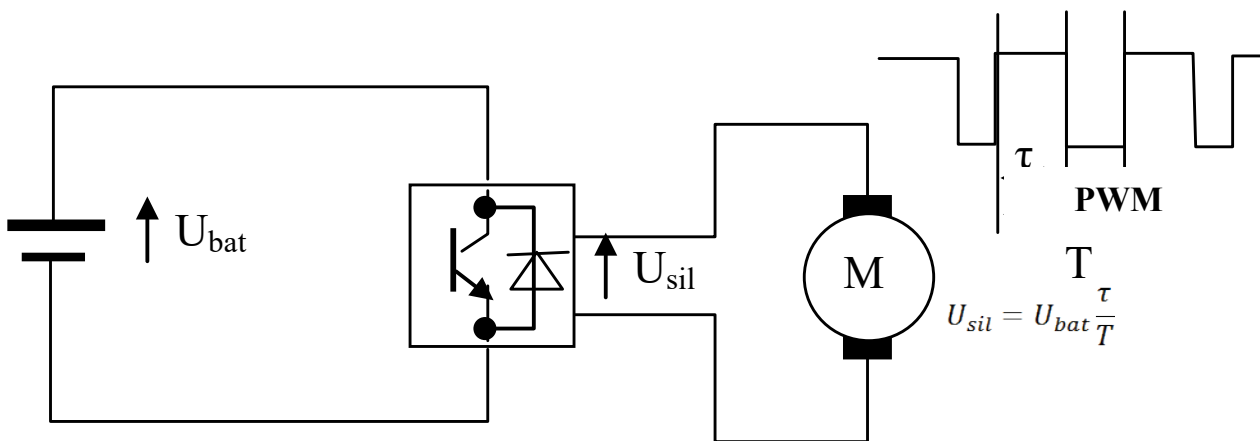


Fig. 3. Diagram of the PWM method control system

The impulse which was drawn from the storage cell due to the auto-transformation phenomenon (maintaining of continuous flow of electric current due to inductance, at the lack of supply voltage – through generation of self-inductance voltage, providing the effect of averaging of the effective voltage value with the PWM method) amounts to, approximately:

$$U_{sil} = U_{bat} \frac{\tau}{T} = U_{bat} PWM, \quad (2)$$

$$Q_{bat} = \frac{(U_{sil} + \sum \Delta U_{TR})}{U_{bat}} Q_{sil}. \quad (3)$$

Assuming that:

$$U_{sil} \cong U_{sil} + \sum \Delta U_{TR} = PWM U_{BAT}, \quad (4)$$

where: PWM is the relation of time of opening the τ transistor switches transporting the voltage from storage cells onto the motor terminals to the duration time of the T cycle.

We may note that:

$$Q_{bat} = PWM Q_{sil}. \quad (5)$$

In the case of a fixed motor speed, as the voltage on its terminals is proportional to the rotary speed, which it rotates, it is possible simply to say that the draw of an impulse from the storage cells will be smaller for low speeds than at high speeds for the same load moment. It means that draw of an impulse from the storage cell in time is proportional to the power actually consumed. At omitting, the change of the system has efficiency for different speeds and loads. This rule applies also for the locking process, where the voltage $U_{sil} > PWM Q_{BAT}$. Then the current flows from the engine to the storage cell.

In linear drives utilising self-locking screws, the process of reclaiming the energy is ineffective. It is possible to assume that such system is powered in both ways and the energy during turning is dispersed in the mechanical system. Despite that, the work performed by the engine is not much lower than the energy drawn from the storage cell and depends on both the distance and resistance to movement. In the case of electric drives, we are dealing with small energy cost of control Kes_e of the electric system – which is consumed by the semiconductor switches and increased with the energy consumption by the control and regulation systems (KR).

$$Kes_e = \sum \Delta U_{TR} Q_{sil} + KR. \quad (6)$$

In the case of a classical hydrostatic drive with solenoid valves proportional to the servo type, powered from the hydraulic storage cell, the cylinder is propelled with oil filling its chambers (Fig. 4). Speed control of the piston rod of the cylinder is executed by suppressing the oil flow in the valves. Only such amount of oil is taken from the storage cell as flows into the cylinder, while the “pressure surplus” is dispersed in the valves, where the controlled energy losses occur.

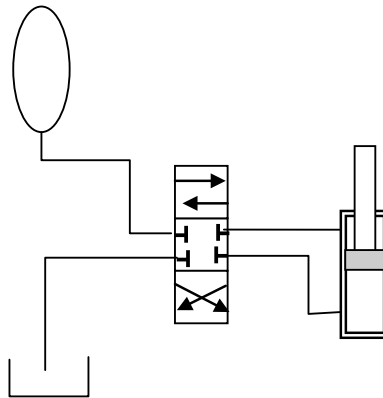


Fig. 4. Diagram of a hydrostatic system powered from a storage cell

Hence, the energy taken from the storage cell depends on the displacement of the hydraulic cylinder and not on work performed by it. The energy surplus will transform into heat in the solenoid valves suppressing the flow. Assuming large enough hydraulic storage cell, the volume of which far exceeds the absorbency of the cylinder, we may note that (for simplification assuming equal surfaces of the piston at the rod and rod-less side):

$$p_{acc}\Delta q_{acc} = \Delta p_{sil}q_{sil} + \sum \Delta p_{zaw}q_{sil}, \quad (7)$$

$$p_{acc}As_{sil} = \Delta p_{sil}As_{sil} + \sum \Delta p_{zaw}As_{sil}, \quad (8)$$

$$p_{acc}As_{sil} = F_{sil}s_{sil} + \sum \Delta p_{zaw}As_{sil}, \quad (9)$$

where:

- p_{acc} – pressure in the hydraulic storage cell,
- Δq_{acc} – decrease in volume of oil in the storage cell,
- Δp_{sil} – decrease of pressure in the cylinder,
- q_{sil} – flow of oil through the hydraulic engine (cylinder),
- A – surface areas of piston of cylinder,
- F_{sil} – force applied to piston rod of the cylinder,
- s_{sil} – displacement of piston rod of the cylinder.

The energy cost of controlling the hydrostatic system Kes_h may be presented as:

$$Kes_h = \sum \Delta p_{zaw}As_{sil} + KR, \quad (10)$$

$$Kes_h = \left(p_{acc} - \frac{F}{A}\right)As_{sil} + KR. \quad (11)$$

Hence, to improve efficiency of the system it is necessary to aim at as low as possible pressure surplus in the storage cell in relation to the pressure needed to generate the required force (taking into account the surplus needed for control).

In the rotating hydrostatic drive systems, we are often faced with adaptive systems of the load-sensing type or the systems with engines with variable absorbency. Their principal of functioning is based on the change of gearing within the machine, through application of swivel heads with variable pendulum angle.

There are no similar solutions in the case of linear systems.

4. Variable configuration systems

Analysing behaviour of the living beings developing their way of movement in the course of millions of years of evolution, we may come to many interesting conclusions concerning algorithms of movement. So far, any attempts to create a walking machine, which would be equally energy efficient as living beings, were unsuccessful.

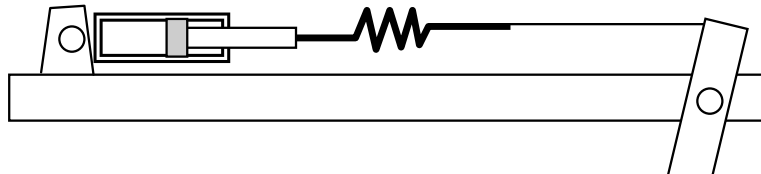


Fig. 5. Band driving system with spring elements analogical to the muscular-skeletal system of a human

Imitating the “driving system” solutions in living beings is possible to create a band system with spring elements (Fig. 5), which will mimic muscles and tendons. Humans and animals make a perfect use of the gravity force to propel their bodies. They change configurations of their own body putting it off balance and transform the kinetic energy into elastic energy of muscles and

tendons. Following this logic, an analysis was made of the human way of movement, especially from the point of view of walking robots serving as exoskeleton for humans.

At present, when writing about hybrid drives, we think about diesel-electro or diesel-hydraulic drives. However, the hybrid drives with spring elements have been known for ages.

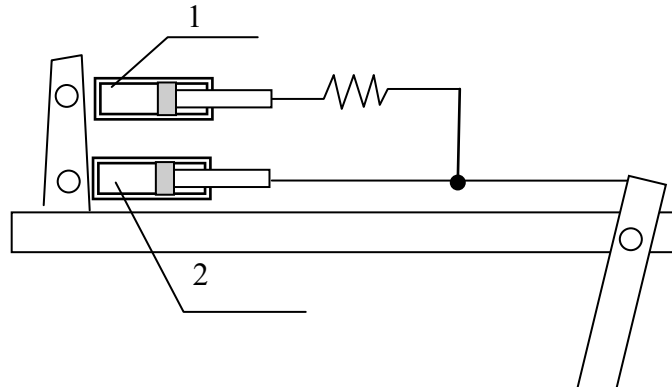


Fig. 6. Parallel band drive system with spring elements

The springs serve as the so-called burden reducers in the system, which allows application of a drive system with greater power, and therefore with smaller size and weight. Limbs of walking machines may be propelled with the use of gear motors, engines, actuators connected directly to the propelled points through bands. The drive systems situated close to points of limbs cause an increase in weight and moment of inertia of the limbs, and are an unnecessary burden for drives of other points.

Utilisation of spring systems enables to compensate gravity in a specific limb system, at least to a certain extent of movement. Leading the bands connecting springs with the propelled element through blocks with variable transmission facilitates adjustment of the characteristics of the created forces to the needs. Change of the system configuration may involve performance of some work. Application of variable configurations of the power transmission system is a very promising and often used solution, for example, in the recurve bow systems, where the ratio of driving forces changes with the draw force of the bowstring.

Hybrid spring-hydraulic drives may have the form of serial (Fig. 5) or parallel systems (Fig. 6). In the system showed in Fig. 5, cylinder 1 is responsible for the initial tension of the spring and therefore for the force which supports the system.

Utilisation of the band systems with hydraulic cylinders and variable gearing may improve effectiveness of hydraulic drive systems (Fig. 7). Configuration of such a system may be variable in relation to the load and change automatically according to the construction and principal of functioning of the mechanism or may be controlled by an independent system executing the prepared algorithm.

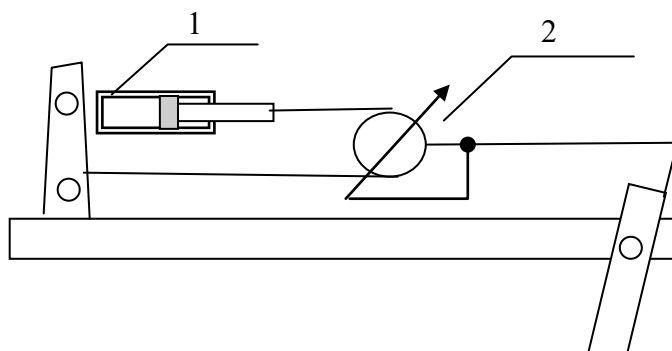


Fig. 7. Band drive system with a variable transmission gear (2)

Building a hydrostatic linear system with variable transmission may significantly improve effectiveness and energy efficiency and may even enable reclaiming energy.

Fig. 8 presents a proposition of a drive system with variable transmission. The cylinder (1) is the driving elements. It propels the intermediate band wound onto the gears with variable transmission (2). The hydraulic cylinder (3) is responsible for the change of the characteristic of the system. It operates on the basis of the proposed control algorithm. Analogical system is the one presented in Fig. 7. The difference is in the manner of control. The system in Fig. 7 is self-adjusting to the load applied to the system.

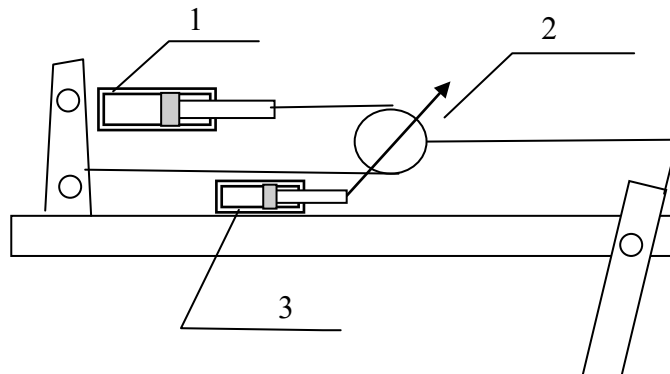


Fig. 8. Band drive system with a variable transmission gear

5. Simulation result

Drawing from the construction and functioning of the movement of a human body, it was decided to build a hybrid drive system. Fig. 9 presents computer model of one of the proposed solutions of the drive for a walking machine developed under the project entitled “Egzoszkielec” (DOBR/0037/R/ID1/2012/03), created in the *Adams* program. This is a hydrostatic system powered from a storage cell. Hydraulic cylinder moves the band, which is connected with the propelled element through a block. The mechanism was installed with a spring. Its purpose is to introduce flexibility to the system. As a result, the system is able to adjust to the load through change in the length of the arm of the force, hence changing the transmission of the lever system. The spring system also suppresses surges of forces and cumulates energy.

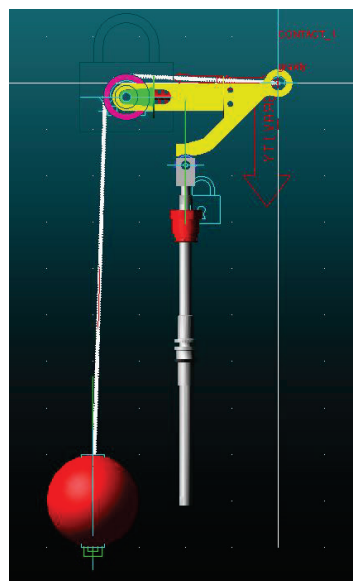


Fig. 9. Computer model of the exoskeleton drive system

The prepared model was subjected to simulations. During the simulation, piston rod of the cylinder was protruded by 60 mm. The test examined the maximum height to which the given load will be lifted. The simulations assumed the spring rate of $k=10$ N/mm. Sample runs of the simulations were presented in Fig. 10 and 11. In the first case, the load applied to the system amounted to 40 kg, in the second to 10 kg.

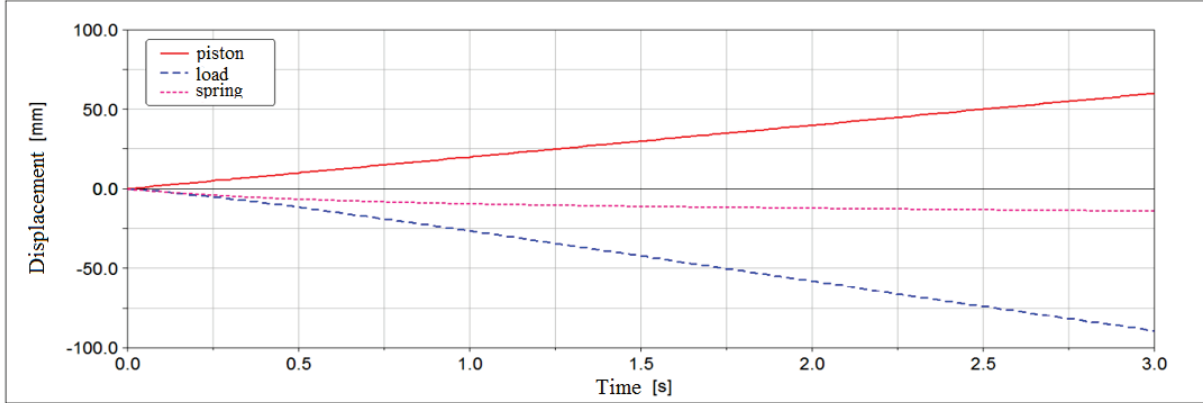


Fig. 10. Simulation results for the 40 kg load

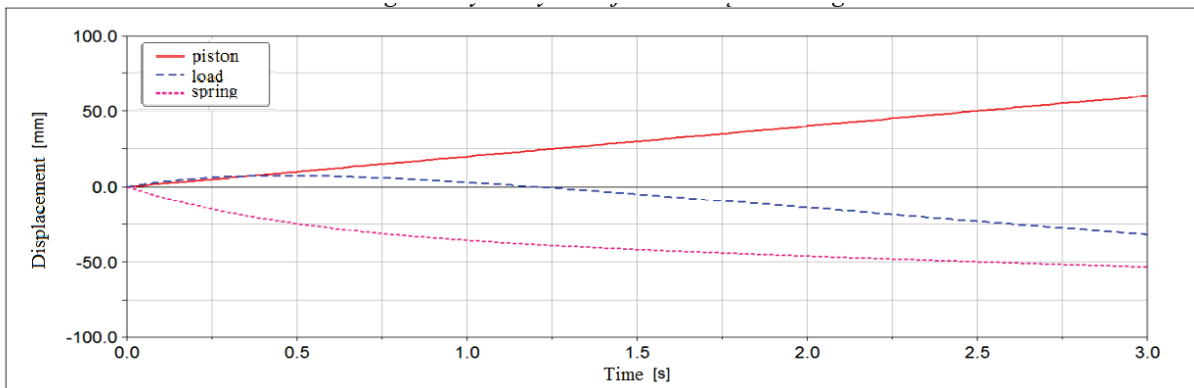


Fig. 11. Simulation results for the 10 kg load

The cylinder piston rod stroke was presented in the graphs with continuous (red) line. The dotted line curve (blue) presents vertical transmission of the load suspended on the band. Deflection of the spring was recorded with the dot line. Fig. 12 presents the aggregated results of the simulations.

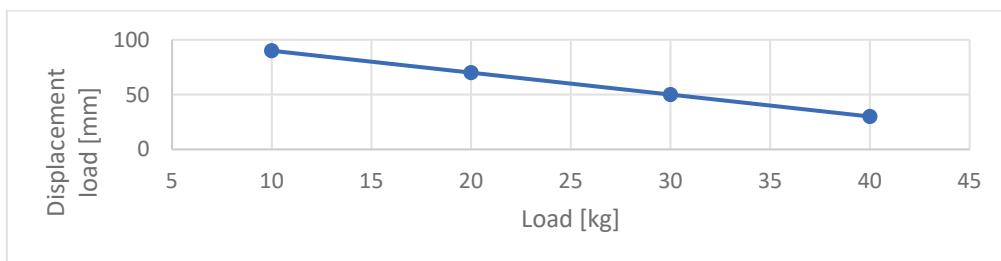


Fig. 12. Simulation results

Analyses suggest that the system has the ability to adjust to the load applied. If we assume that, for the full load, the range of displacement of the end of the band is sufficient for performance of the system's work, and then shorter piston rod stroke is sufficient for partial loads. This means energy conservation amounting to approximately 30%.

6. Conclusion

Mimicking algorithms and the way of movement of the living beings may improve effectiveness of the drive systems of walking machines. Introduction of spring elements in the form of bands is a relatively attractive solution. As a result, the weight of driving elements does not constitute an additional burden for the propelled elements. Moreover, they suppress surges of the load and have small volume.

New materials enable increasingly accurate mimicking of the nature and properties of tissues of the living beings and their way of movement.

Due to the application of the elements with variable transmission, it is possible to increase effectiveness and efficiency of the whole drive system.

It is possible to build simple lever systems with variable transmission, which significantly improve efficiency of the hydrostatic linear drives.

The proposed system has improved the efficiency in the tested cycle by 30%.

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