Design and Movement Control of a 12-legged Mobile Robot

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Jacek Rysiński, Bartłomiej Gola, Jerzy Kopeć

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Abstract:
In the present paper, design and performance of 12-legged walking robot is described. The complete technical specification was developed for the proposed solution. The analysis of stability of the robot movements was undertaken. Communication between robot and operator is based on remote control procedures performed by means of own software which is written in versions for smartphone or desktop computer. The software version for desktop computers has additional useful features i.e. monitoring of the area of robot work/activity via a wireless camera mounted on fore side of the robot.

Keywords: *mobile robot, design, control, kinematic analysis*

1. Introduction

Specialized mobile robots are produced and utilized all over the world. Their typical range of applications is as follows: monitoring, repair routines, inspection of chemically contaminated (or under threat of contamination) areas, extinguishing of fires, detecting and removing of bombs as well as various actions against terrorism. Separate but intensively developed area of utilization of such types of robots is: detection and removal of landmines and associated task [2], [3], [4]. Additional applications of mobile inspection robots are tasks performed in pits and coal mines as well as similar location where human life (e.g. machine operator) is in danger, so specialized mobile robots are utilized. In Poland, there are not any robots designed and/or manufactured for such applications. Particularly, robots for anti-terrorist actions are needed in Poland where the demand of these devices is on par with other countries.

All these devices have one common feature i.e. movement/drive system which enables performance of their movement.

The goal of the present work was to design and manufacture of walking robot together with some cooperation elements e.g. control system where control routines are performed via a modern phone (iPhone), tablet, notebook or desktop computer.

2. Mechanical Subsystem of the Robot

Within the design phase of the DUODEPED robot, the ideas of motion based upon wheels or caterpillar tracks where excluded. On the contrary, the mechanism of special legs presented in 2005 in Austria by Dutch physicist Theo Jansen was applied. The concept of the design solution is based upon utilization of simple geometric figures which are mutually connected by means of nodes (Fig. 1). The point – marked by means of blue color (1’) – is fixed on the rotation axis; the element which passes power is marked as green (2’). The device is driven into a motion which enables performance of consecutive steps via the node of a triangle which has contact with the ground.

Time of contact with the ground for an orange node (3’) is equal to the time of the 120° rotation of the green node around the driving shaft. Taking into account that one full rotation is equivalent to 360°, aiming for sufficient stability of the device, the number of pair of legs (Fig. 1c) assigned to one rotation cycle was assumed as equal to 3. Therefore their driving bands are mounted on the driving shaft fixed for every 120°. This design solution allows for perma-

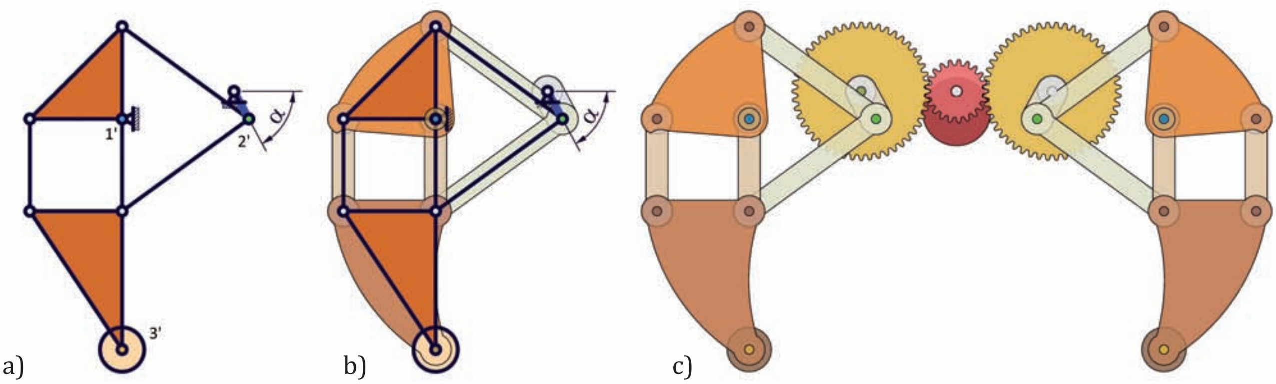


Fig. 1. Concept of robot legs

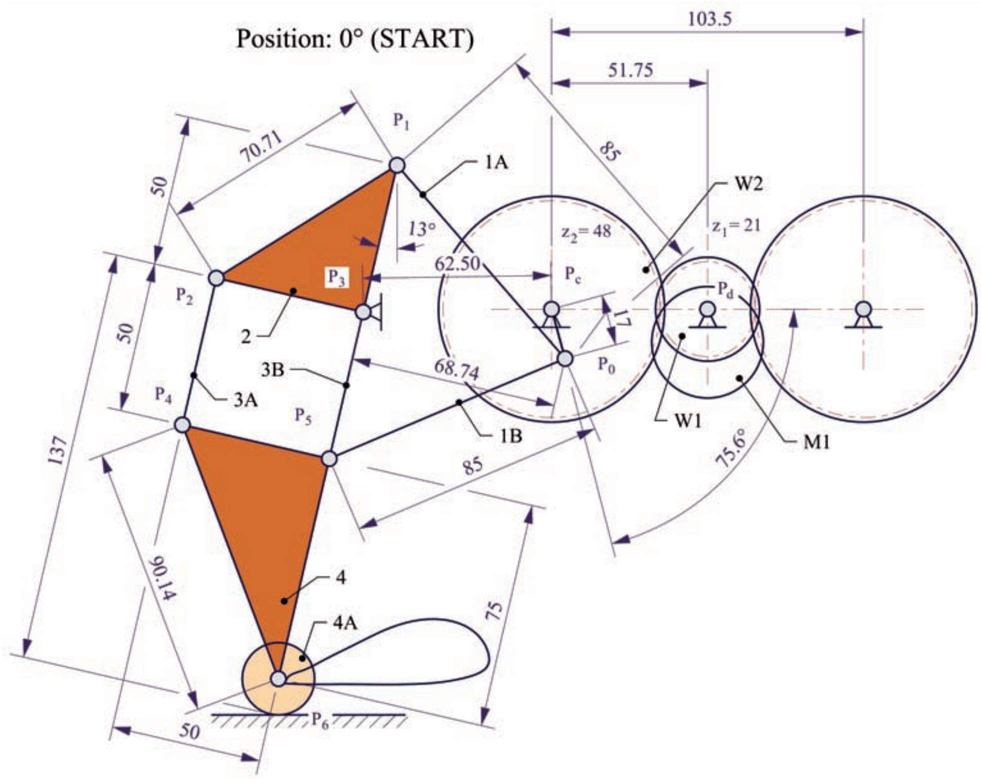


Fig. 2. Kinematical scheme of single robot leg and trajectory of wheel axis

nent contact of the legs with the ground, moreover it creates the base for stable walking.

2.1. Legs, Their Number and Motion Trajectory

The robot legs consist of triangles connected by bands. Their special shape (geometrical properties) allows for performance of leg movement trajectories, in such a manner that during the performance of a step – point P6 moves parallel to the ground, giving an impression of smooth motion as well as assuring stability of performed robot steps.

Each robot leg consists of 40 elements, the elements can move. Aiming for reduction of friction, the legs are mutually separated by means of separators (washers) made of Teflon having thickness 0.5 mm. Moreover, aiming for reduction of the size – instead of ball bearings, sliding bearings were utilized being a brass rings mounted on shafts.

2.2. Design Solution of the Robot Leg

Using the above described ideas, a design solution has been proposed which assures minimal number of support points. Therefore, 12 legs were designed which are grouped in four sets of three legs. The design solution has a property that in a special case of motion (ahead) and the special legs arrangement – the number of these supports increases to eight, whereas remaining four legs are in the middle of the cycle of displacement of the support point over the ground.

The design solution according to Theo Jansen's idea allows for permanent contact of minimal number of legs with the ground. However, due to the fact that the center of gravity is placed in a relatively high position and simultaneously the support points are placed (distributed) closely to themselves – the construction is not fully stable. Aiming for improvement of construction stability – the leg mounting points were displaced in a distance of 194 mm (Fig. 3).

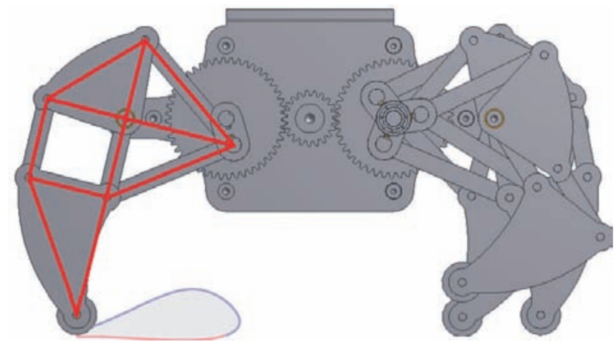


Fig. 3. Design solution for fixing robot legs

Due to the change of positions for fixing the robot legs, the drive element (module) was designed as a system of two co-operating crankshafts placed symmetrically (180°). Their consecutive cranks are shifted mutually by an angle of 120°, around the main rotation axis. Their drive system was coupled with the gear wheels of a gear having the ratio equal to 2.29. The advantages of the proposed design solution of the robot consisting in 12-legged walking system are as follows: high capacity of loading, relatively high velocity of motion and ability to overcome the obstacles – preserving simultaneously stability of the whole structure.

2.3. Kinematical Analysis of Robot Leg

The analysis of robot movement is performed using a few assumptions. Every linkage is not compliant. All kinematics pairs are without backlash. All the movements were projected to one plane. All activi-

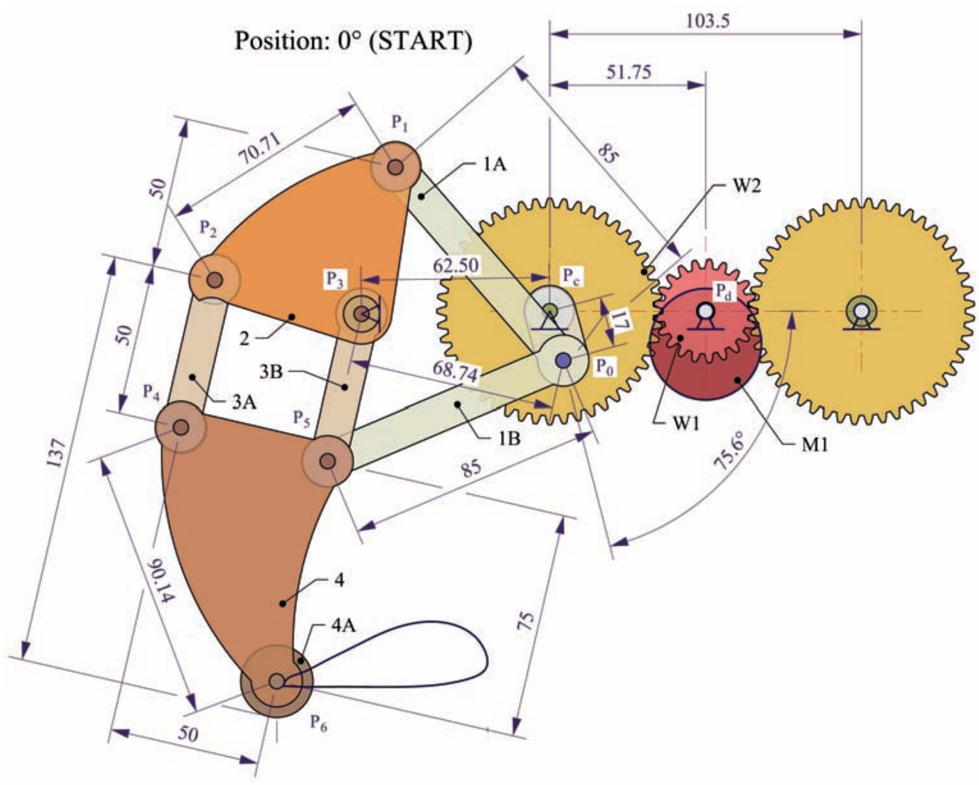


Fig. 4. Main dimensions of leg and its drive mechanism

ties were performed using such kinematical scheme of mechanism.

The first stage of analysis was finding out the configurations of linkages for selected positions of driving crank. The results are depicted in Fig. 5. The path of movement of point P6 (which is corresponding to axis if ground wheel) was obtained by connecting subsequent positions of point P6. Notice that this tra-

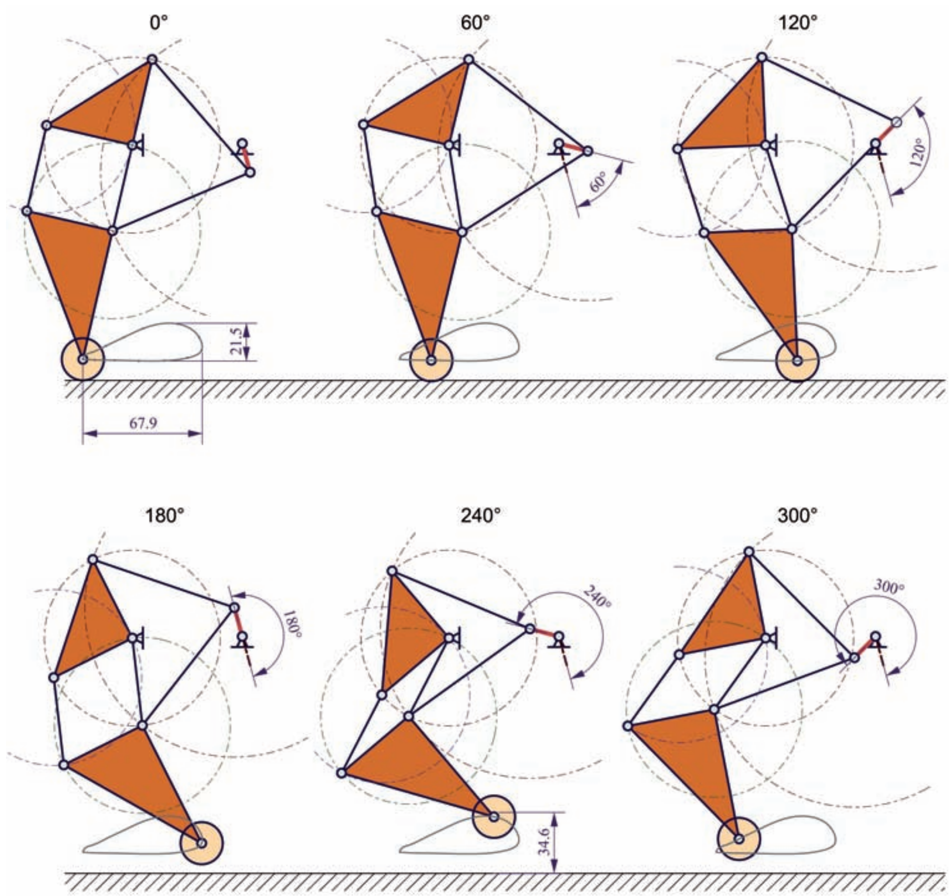


Fig. 5. Single leg movement, for selected positions of crank

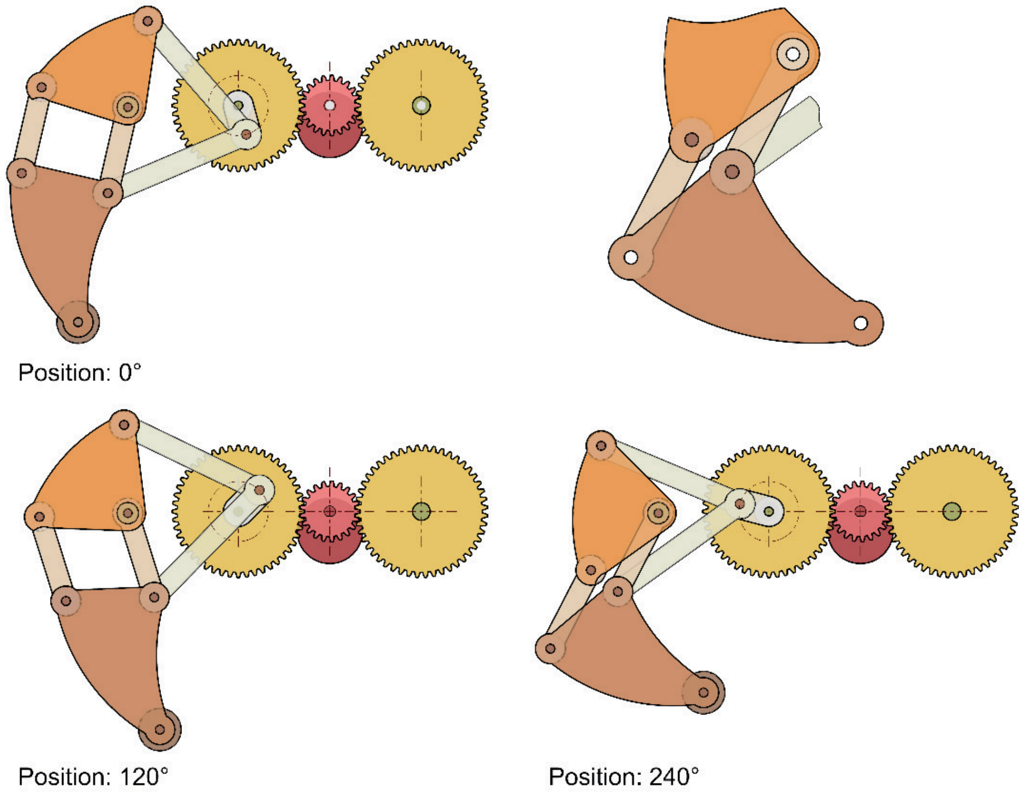


Fig. 6. Free positions of robot legs driving mechanism

jectory was drawn up with respect to point Pc. Additional drawing (Fig. 6) shows positions for 3D CAD model of mechanism. Using such methodology the design of linkages was optimal and the risk of parts collisions and other design troubles were prevented.

The second stage of analysis was revealing the velocities in all joints of robot leg. The graphical method was used and the results are shown in Fig. 7 and Fig. 8.

The results of analysis (i.e. obtaining the shape of trajectory, knowledge of accurate positions of linkages and ground wheel, velocities plans) ensured the selected design and facilitated it. Velocities collected in table 1 were determined for angular velocity of crank ω_0=5,09 rad/s.

Figure 9 shows the selected position of the leg with marked centre of gravity (CG). The full path of mechanism motion was traced.

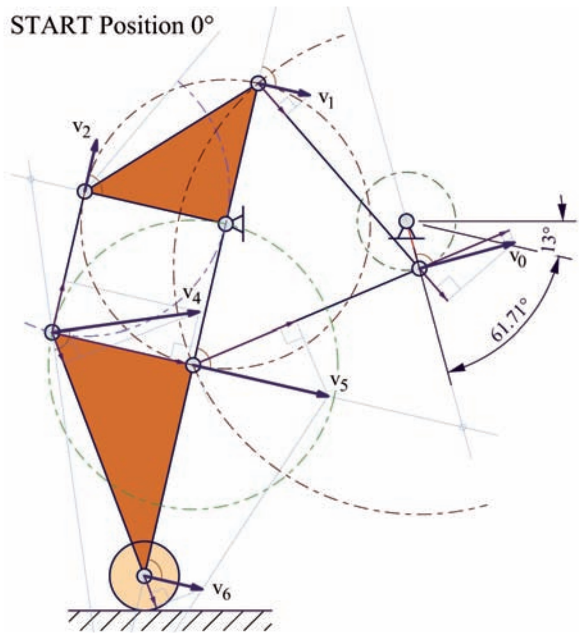


Fig. 7. Velocities of joints for position +0°

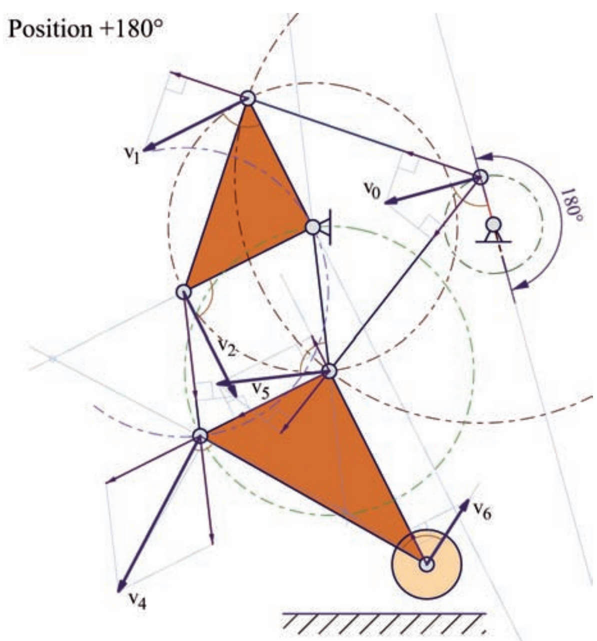


Fig. 8. Velocities of joints for position +180°

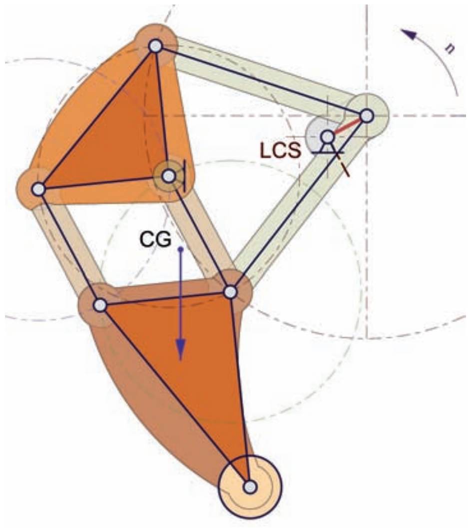


Fig. 9. Exemplary position of gravity centre for leg during the motion (angle coordinate 90°)

Table 1. Sample numerical values of joint velocities [mm/s]

Velocity	Position	
	0°	180°
v_0	86.5	86.5
v_1	46.3	102.1
v_2	46.3	102.1
v_3	0.0	0.0
v_4	130.2	154.7
v_5	121.6	98.8
v_6	52.1	67.1

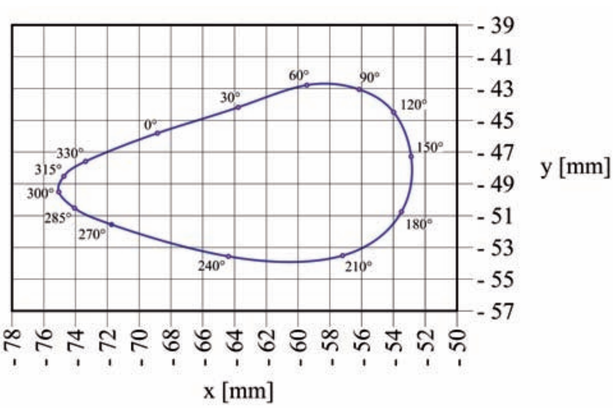


Fig. 10. Changes of gravity center of single leg mechanism

Figure 10 shows changing the position of gravity centre for single leg mechanism during the motion. Simulation was performed for angle from 0 to 360 deg. The results were obtained numerically from CAD model of mechanism, with assumption, that the mechanism is planar.

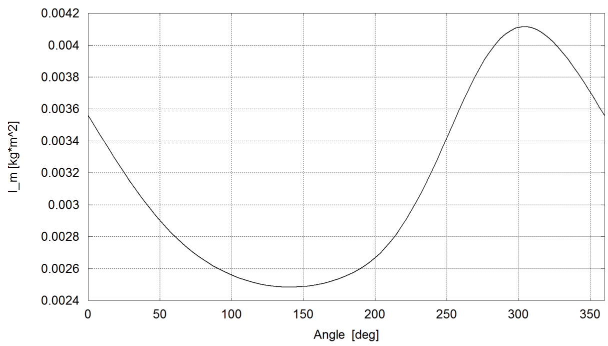


Fig. 11. Reduced mass moment of inertia with respect to crank axes

According to computer simulation the Figure 11 shows the variability of reduced mass moment of inertia with respect to crank axes was obtained. This is the plot for single leg.

2.4. Stability of Motion

Multi-leg constructions moved usually in a motion (walking) which is statically stable. During such walking, the projection of the robot center of gravity is always placed inside the polygon of supports (Fig. 12 a). The stability spare range is defined as a distance between the projection of the center of gravity and an edge of support polygon. This distance is measured along the current vector of motion of the center of gravity (Fig. 12 b).

The stability spare range – for statically stabile walking – should not be lower than value called as minimal margin. The margin should be set in such a way that all neglected dynamical effects and action of external forces do not cause any loss of robot stability. The best situation is when this stability spare range is determined experimentally. The velocities of motion of the contemporary walking robots or devices are relatively low, usually lower than several kilometers per hour (sometimes even less than 1 kilometer per hour). Therefore, the assumed simplifications are acceptable.

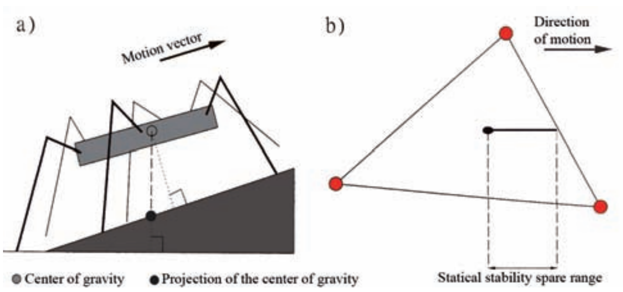


Fig. 12. a) Projection of the center of gravity during motion through an inclined slope, b) Statical stability spare range for 3-support walking

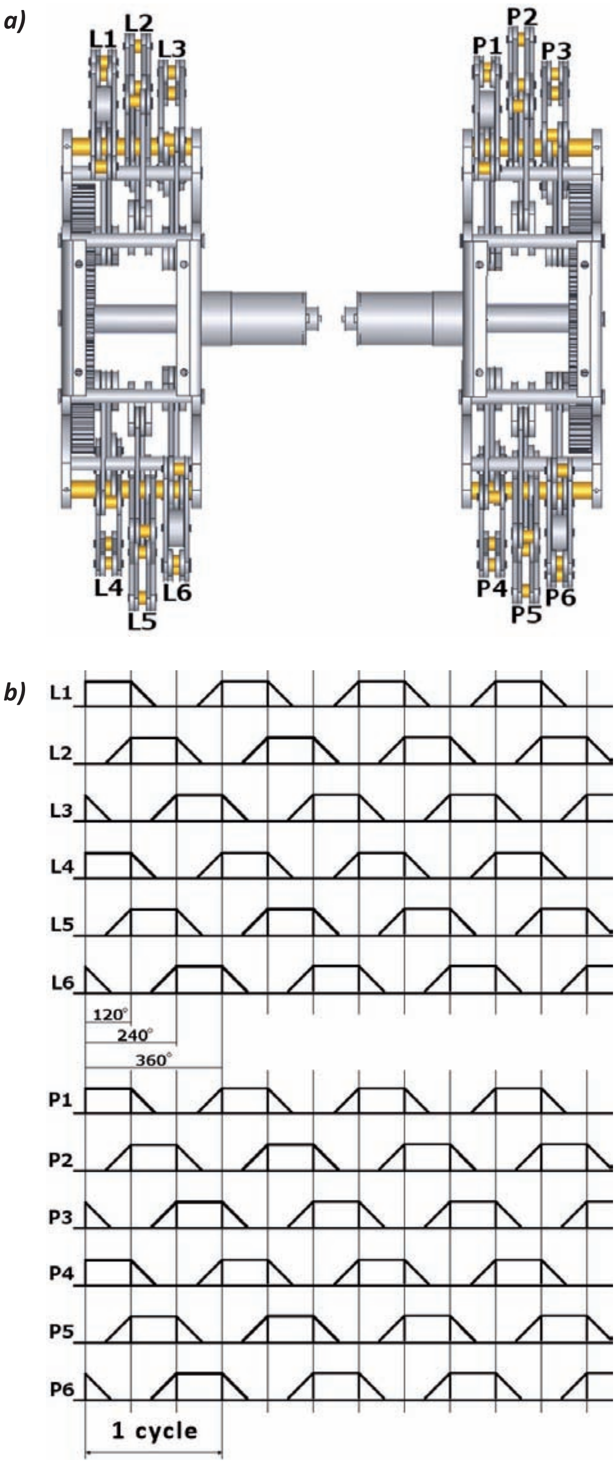


Fig. 13. a) L1 … L6, P1 … P6 – Designation of legs; b) diagram of a robot foot contact with the ground

As can be seen, the criterion of the stability spare range does take into account configuration (shape) of a machine as well as properties of the ground. The sufficient margin of stability is defined taking into account a possibility of reduction of the expected support polygon due to lack of one point of support (lack of contact for one arbitrary leg). If the machine (robot) is supported by n legs, then – besides the proper polygon – other polygons of support are created and considered in the prepared software. These polygons are adequate for all other possible phases (versions) of support by means of (n – 1) – legs. The sufficient polygon of support is built as common area of all n – 1 polygons. Sufficient spare range of stability is measured in a way described above – therefore it could be considered for machines or robots having more than four legs.

The statically-stable walking of the designed 12-legged robot – consists of three 4-support phases (Fig. 13). This solution assures permanent contact of 4 legs with the ground, therefore there is not any threat of loss of stability. The crankshafts – which driver the robot legs – are connected via the gear. In consequence, only one type of walking is possible where the only variable is its velocity. Due to the motion of the robot legs, its center of gravity slightly changes the position. The changes are so low among other – because the legs' mass is relatively low in relation to the whole mass of the construction (20% of the whole mass) and an effect of application of crankshafts – mutually rotated by 180°. The last mentioned property assures that the legs of opposite sides balance themselves. Slightly different are the matters according to the spare range of stability, which varies essentially during motion of robot legs. It is caused by the changes of the distance between the legs' contact points with the ground and the robot center of gravity [8], [9], [10].

The measure of energetic stability of a particular robot position is the minimal work, which has to be done via whichever disturbing factor/activity causing destabilization of its current position. It is the work dedicated to displacement of the gravity center of the robot to such new position – in which, the gravity center is placed in the vertical plane above the edge of the support polygon. The distance is preserved within a particular time. Therefore, it is ultimate stable position (having ultimate stability). In consequence, any

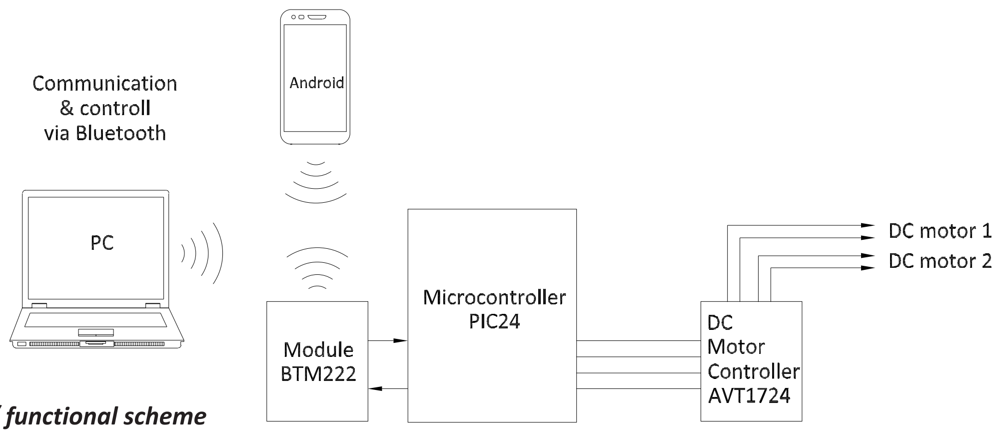
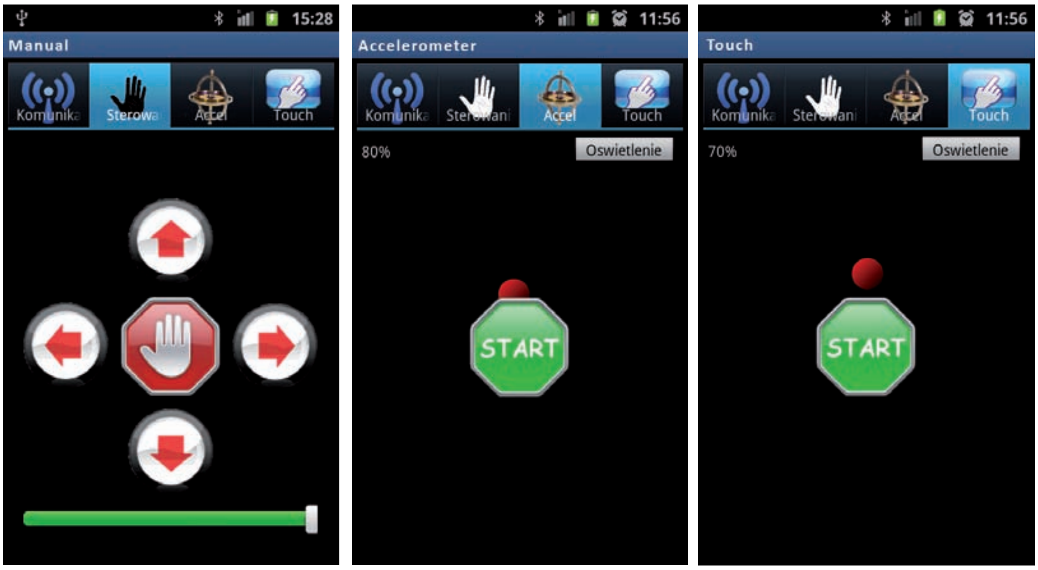


Fig. 14. Layout / functional scheme



a) b) c)

Fig. 15. Screens dedicated to the control system: a) manual control; b) control using accelerometer; c) control using touch screen

smallest disturbance will cause overturning of the robot. This work, in physical sense, is equivalent to the difference of potential energy of the gravity center adequate for the start and end positions of the robot.

3. Electronic Subsystem of the Walking Robot

Robot control routines should be intuitive and easy to perform for persons of different age groups. In general, control should be simple and additionally its visualization should be possible. Nowadays, for some people, it is even unimaginable to design such a device without control visualization [7].

Aiming for increasing comfort and ease of robot control, the control system was based upon wireless transmission of data via Bluetooth. Due to this solution, cables are obviously not needed; nevertheless remote control is possible from relatively high distance. The distance considered is equal to 100m on an open area, depending on possibility of propagation of radio waves. A device – which could be used for robot control – can be based on Android 2.3.6 system as well as upgraded ones mounted in e.g. smartphone, tablet or other devices based on Windows operational system e.g. notebook or desktop computer [6]. The necessary requirement is that the device is equipped in Bluetooth module.

Central subsystem of DUODEPED is the effective microcontroller PIC24HJ256GP610 made by Microchip company [1]. Special program was written in C algorithmic language, which was compiled by means of compiler C30. Microcontroller performs communication utilizing the serial transmission UART type via Bluetooth BTM-222 module which assures radio connection with the control device (subsystem) [4]. The functional scheme enclosing all elements i.e. from the control device up to motors – is presented in Fig. 14.

The robot control system was written using the Basic4Android software. It allows for control of the robot via three working modes.

The first of available control work mode is the most simple control version (Fig. 15a). It is equipped with the direction arrows as well as hidden arrows responsible for motion along curves or bands. Depending on the chosen direction of robot motion, the robot will be moved ahead, turn back at the spot and turning along the arc/band.

The second method of control (Fig. 15b) utilizes the accelerometer gauge which is available in a smartphone. Just declining the device, the adequate information about the position of phone is transmitted. If the robot motors are triggered via a button START, then the robot will perform the motions in accordance with the declining of the control device. The third, i.e. the last control mode (Fig. 15c), performed by means of Android, utilizes the touch screen. The clicks on this screen ensure the robot starts its motion if only the option START has been earlier clicked – launching charging of the robot motors.

Robot control software for desktop computer (PC) or notebook.

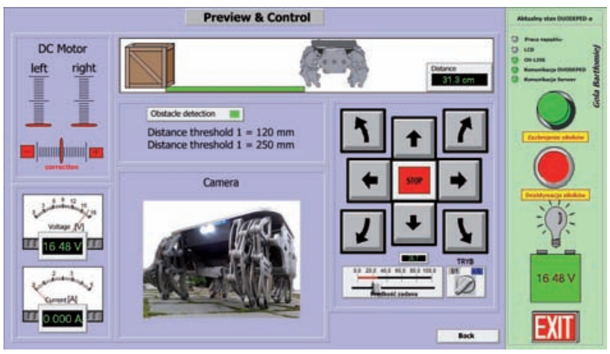


Fig. 16. Screen „Preview & Control"

Control of DUODEPED robot could be performed by means of a desktop computer or a notebook when the software inTOUCH version 10.1 is mounted (Fig. 16).

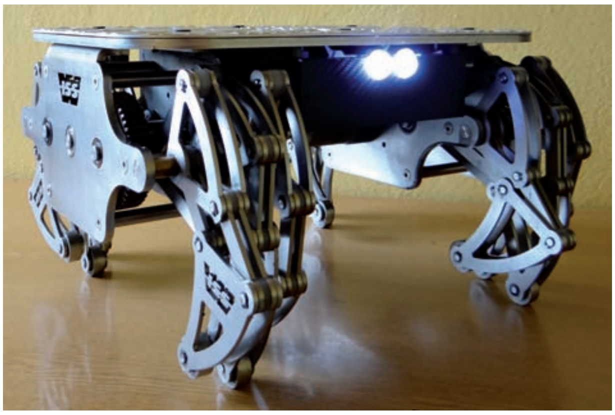


Fig. 17. DUODEPED – 12-legged walking robot

Moreover, the DASMBSerial.2 of the package ArchestrA creates the communication system used for control purpose.

After triggering of the application, a user must log in using one of the available accounts. The login options and passwords are gathered in the field „PIERWSZE KROKI" (introductory steps). For the service activities, the password is hidden and it is the same as login.

The control of robot is performed in intuitive way. It is enough to log in as a user and the button „Preview & Control" is activated. Via this button, the window of control is open. In this window, we can chose the measurements of the voltage of the battery mounted in machine/robot and measurement of electric current which flows through the controller of DC motors and charges theses motors.

In the upper part of this window, there is a monitoring field shown in right part of the discussed window. Moreover, monitoring is available in visual way as a moving construction.

The window is zoomed from 0 up to 50 cm, therefore above this distance the pictogram of construction on visualization sub-screen (sub-window) will be placed on right side of the control window. The detection of an obstacle option is active by default. Therefore, if during its motion the robot approaches on obstacle for the distance lower than the second threshold – then its velocity in this direction is diminish. But if the distance towards the obstacle further diminishes and it overcomes the threshold 1, then the drive mechanism: (a) stops the robot, (b) changes the direction of rotations and (c) it moves back with a low velocity (reduced to 20%). Next overcoming of the threshold 2, i.e. when the robot remains in safe distance, causes stopping of the robot and waiting for further orders. If we would like to start movement, then first the motor should be activated – i.e. ready to switch the power on. When the robot is not used for a long time, then for safety reasons, the motors should be deactivated – disenabling a possibility of using the robot by chance in unexpected moment.

4. Final Remarks

Mobile robots are more and more frequently utilized by people for differing purposes. Within recent years, mechanisms applied in robotized constructions as well as autonomous robots were successfully used in army, medicine and industrial plants. Since the dynamic development of robotics in modeling activities is observed. People are more and more interested in design and programming of so called personal assistant robots. All over the world, robots are used for versatile tasks e.g. monitoring, production, safety and protection. It can be stated that nowadays robots are everywhere. Several times a year, presentation events and robot contests are organized in Poland and abroad. In these events, robots designed by private people as well as by firms take part. It is worth nothing, that every year number of participants of such tournaments increases very fast.

The manufactured 12-legged walking robot – DUODEPED – had won several prizes for the design itself and innovative design solutions. Its name is created based upon the Latin i.e.: taking into account words: DUODE – *twelve* and PEDES – *legs*. It is a new name which has never been used – which could be confirmed via search results of the popular web/internet browsers. The construction has been manufactured very solid, which could be confirmed by a possible of displacement of relatively high loads (approx. 100kg). Robot has many admirers and it has a circle of fans i.e. students as well as kids who can play endlessly.

AUTHORS

Jacek Rysiński* – Faculty of Mechanical Engineering and Computer Science, University of Bielsko-Biala, Bielsko-Biała, Poland.
E-mail: jrysinski@ath.bielsko.pl.

Bartłomiej Gola – Faculty of Mechanical Engineering and Computer Science, University of Bielsko-Biala, Bielsko-Biała, Poland.
E-mail: bartlomiejgola@wp.pl.

Jerzy Kopeć – Faculty of Mechanical Engineering and Computer Science, University of Bielsko-Biala, Bielsko-Biała, Poland.
E-mail: jkopec@ath.bielsko.pl.

*Corresponding author

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