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IDEA OF A QUADRUPED WHEEL-LEGGED ROBOT

In order for a quadruped robot to be able to move on wheels while keeping its platform in horizontal position, and to walk, the kinematic system of its limbs should be so designed that each of the wheels has at least four degrees of freedom. Consequently, the designed system will have many DOFs and many controlled drives. This paper presents a novel solution in which, thanks to a suitable limb kinematic system geometry, the number of drives for the robot travel function, i.e. travelling on an uneven surface with the robot platform kept horizontal, has been reduced by four which are used only for walking. The robot structure, the required geometry of the limb links and the driving torque characteristics are presented. Moreover, an idea of the control system is sketched. Finally, selected results of the tests carried out on the robot prototype are reported.

1. Introduction

Research into mobile robots able to move in various terrain and the design of such robots have been intensively developing for at least a decade now. The robots' locomotion systems are based on caterpillar, wheeled and walking undercarriages and sometimes on their combinations. Wheeled undercarriages with wheels capable of large movements are particularly interesting. This design allows the robot to move as a wheeled vehicle or, if necessary, as a walking machine. Besides the well-known Sojourner Martian rover, one can mention here the four-legged robot called WorkPartner [7]. Another idea for negotiating obstacles was proposed for the Shrimp robot,

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which was equipped with additional wheels aiding in negotiating obstacles [9]. Other examples of hybrid robots can be found in [1-4, 6, 8, 14].

This paper presents a wheel-legged robot design with a novel kinematic system for the suspension of each of the four wheels whereby without any loss of traction capabilities the number of controlled drives has been reduced by four. Thanks to this benefits robot has a stable field of stability, witch isn't depended on high of the platform. Moreover the kinematic model is very simple (linear function of vertical displacement of the wheel centre versus the length of the q_1 driver) what makes the control procedures faster.

2. Synthesis of suspension system

The synthesis of the suspension system, aimed at developing a kinematic scheme for the limb mechanism (wheel suspension) was divided into three stages: (1) the specification of operational requirements, (2) the definition of the suspension system design (structure), i.e. the number of links and their connection by kinematic pairs, and (3) the specification of the dimensions of the links.

2.1. Requirements

The robot will mainly move on wheels and the walking function will be used only in special cases. It is assumed that the robot will move in urbanized areas where it can encounter terrain obstacles in the form of slopes, steps and thresholds. It is anticipated that one pair of wheels on one side of the robot will move on a horizontal plane while the other pair encounters a slope, a threshold or a step. It is additionally assumed that the robot may encounter obstacles negotiable by walking over them. The overriding requirement is keeping the platform horizontal all the time.

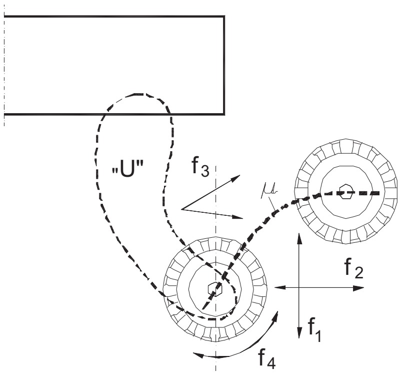

Fig. 1. Required wheel DOFs

2.2. Selected solutions – structural schemes

It follows from the above requirements that the centre of each of the four wheels should be able to execute large movements. In addition, when negotiating thresholds and steps or walking over an obstacle, programmable curvilinear trajectory μ of the wheel centre (Fig. 1) must be maintained. The wheel should have altogether four degrees of freedom and the missing system piece – intermediate chain U – can be easily obtained by structural synthesis methods [5]. The first few possible solutions are shown in Fig. 2.

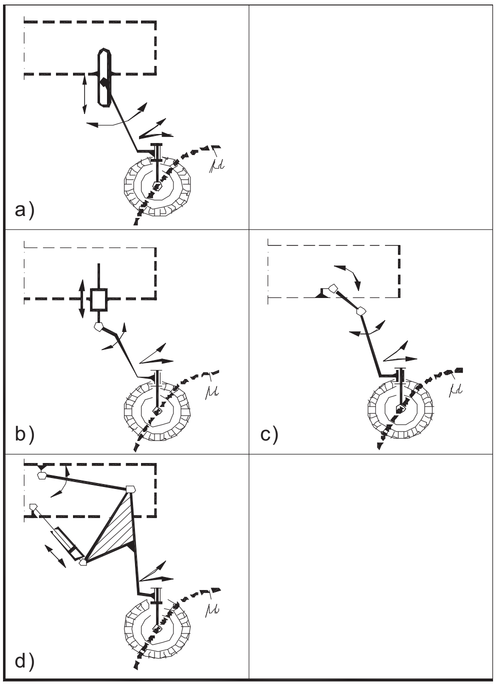

Fig. 2. Selected wheel suspension systems

2.3. Geometric synthesis

The system shown in Fig. 2d was selected from the obtained set of possible solutions. Besides wheel turn and rotation, the steering knuckle has two DOFs. The robot's limb (Fig. 3) is based on four-bar linkage ABCD. Instead of rocker CD which occurs in the conventional four-bar linkage, a link with variable length (servomotor) was used. One of the indispensable drives is servomotor JK which controls the angular position of rocker AB, the other servomotor changes the length of link CD (only for walking).

According to this concept of the limb kinematic system (a system guiding wheel centre E), the platform can be kept horizontal by steering with only one drive q_1. This requires such a four-bar linkage ABCD geometry (dimensions of the links) that the wheel centre (point E of link BC), within a certain range of motion of rocker AB at constant length q_2, moves along a trajectory similar to a straight line segment.

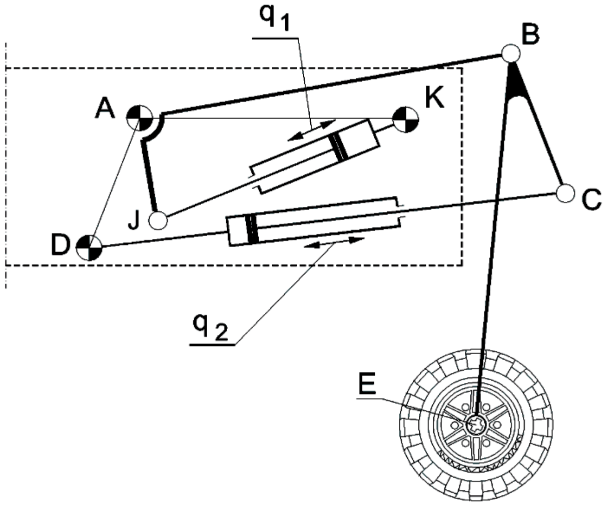

Fig. 3. Kinematic scheme of limb

The dimensions of the limbs were determined for assumed trajectory μ and the corresponding angular displacement of rocker AB. Another aim of the geometric synthesis was to obtain a linear characteristic of the vertical displacement of the wheel centre versus the angular displacement of rocker AB.

The synthesis problem was solved by minimizing the following function

$$Q(\mathbf{x}) = w_1 \sum \left(\Delta X_\mu\right)^2 + w_2 \sum \left(\Delta Y_\mu\right)^2 \tag{1}$$

where w_1, w_2 are scale coefficients ($w_1 + w_2 = 1$) and ΔX_μ and ΔY_μ are the distances of the points of optimized trajectory μ from the expected (assumed) trajectory. The vector of variables x includes the linear and angular dimensions of the kinematic system (Fig. 4). The constraints imposed by singular positions were taken into account in the synthesis.

The geometric synthesis was carried out [10, 11] according to the procedure shown in Fig. 5. The synthesis yields a set of many wheel suspension systems (a few of them are shown in Fig. 6) from which the system with the lowest objective function (1) – best approximating the trajectory to a straight line segment – is selected.

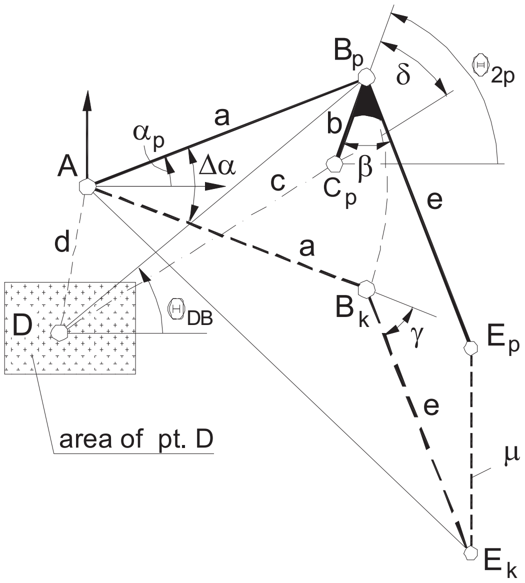

Fig. 4. Parameters of robot limb

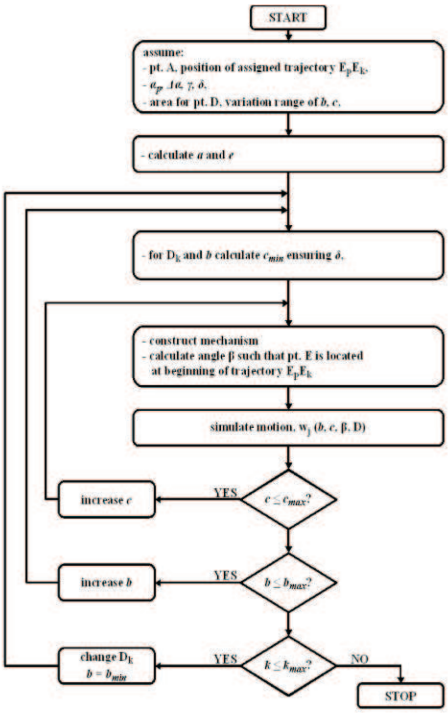

Fig. 5. Block diagram of geometric synthesis procedure

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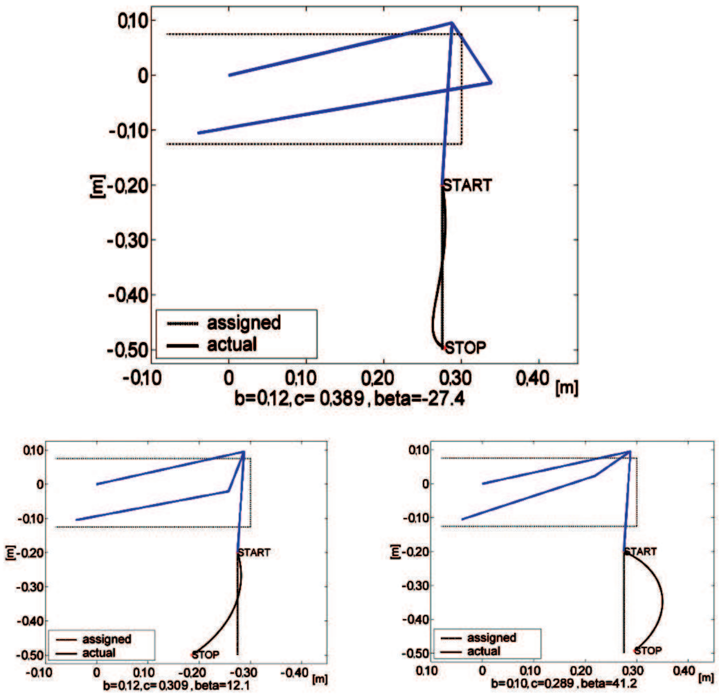

Fig. 6. Examples of limbs with wheel centre trajectories

Thanks to its peculiar geometry, the obtained kinematic system can perform the crucial robot function – platform levelling – using only one drive q_1 in every limb. The second drive q_2 is then a link with a constant length – the rocker of the four-bar linkage. For walking or walking over an obstacle it is necessary to guide the wheel centre along a curvilinear trajectory, which requires controlling the motion of both drives q_1 and q_2.

3. Driving forces

Proper drive motors able to develop the expected torques are needed in order to effectively control the robot. In order to define the motors, the dynamic force analysis equations were used under the following simplifying assumptions:

- as required, the platform is always horizontal and it is assigned coordinate system $\{p\}$ (Fig. 7); only the stages of motion during which the wheel centres move along straight line segments are analyzed;
- the forces acting on the wheel, which originate from the base, are applied in points of contact; for the driving wheels these are two components (normal N and tangent T) while for the wheels without a drive only

the normal force occurs (the tangent component of rolling resistance is neglected);

- the external load consists of the gravitational and body forces resulting from linear robot acceleration $\boldsymbol{a}$;
- the inertia torques resulting from the rotational motion of the members of the robot limbs are not taken into account;
- the limb member weights were included in platform mass m_p; resultant wheel mass m_k, includes the gears and the driving motors.

The external forces and the corresponding radius vectors for the platform (index p) and the front right limb (index pp) are given below. For the platform:

$$\mathbf{F}_p^S = \begin{bmatrix} -am_p\cos\alpha & 0 & -m_p\left(a\sin\alpha + g\right) \end{bmatrix}^T$$

$$\mathbf{r}_p = \begin{bmatrix} r_x & r_y & r_z \end{bmatrix}^T$$

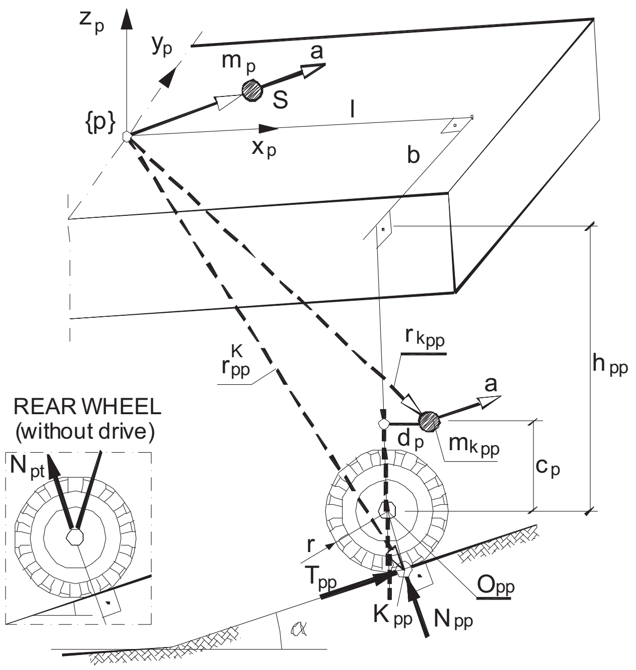

Fig. 7. Scheme of external forces and corresponding robot dimensions

For the (driven) front right limb:
– the force and the radius vector in contact point K_{pp}

$$\mathbf{F}_{pp}^K = \begin{bmatrix} T_{pp}\cos\alpha - N_{pp}\sin\alpha & 0 & T_{pp}\sin\alpha + N_{pp}\cos\alpha \end{bmatrix}^T$$

$$\mathbf{r}^K_{pp} = \begin{bmatrix} l + r\sin\alpha & -b & -h_{pp} - r\cos\alpha \end{bmatrix}^T$$

– the force and the radius vector for mass m_{kpp}

$$\mathbf{F}_{kpp} = \begin{bmatrix} -am_{kpp}\cos\alpha & 0 & -m_{kpp}\left(a\sin\alpha + g\right) \end{bmatrix}^T$$

$$\mathbf{r}_{kpp} = \begin{bmatrix} l + d_p & -b & -h_{pp} + c_p \end{bmatrix}^T$$

In the whole system there are six unknowns put together into this vector:

$$\mathbf{F}_x = \begin{bmatrix} N_{lp} & T_{lp} & N_{pp} & T_{pp} & N_{lt} & N_{pt} \end{bmatrix}^T,$$

where indexes of limbs are: lp – left front, pp – right front, lt – left rear, pt – right rear.

Using the external forces and the forces of inertia for the platform-limbs assembly one gets two equations of forces (along axes x, z) and three equations of torques. The final (sixth) equation is based on the assumption that:

– stiffness values k_i are identical and invariable for the whole range of motion (it was confirmed by measurements),

– vertical displacement Δ of the platform centre (the origin of system {p} in Fig. 7) is an arithmetic mean of displacements Δ_i of the limbs on the diagonals of the platform; hence there is the following relation between the displacements:

$$\Delta = \frac{1}{2}\left(\Delta_{pp} + \Delta_{lt}\right) = \frac{1}{2}\left(\Delta_{lp} + \Delta_{pt}\right),$$

which leads to the equation of forces:

$$N_{pp} + T_{pp}\tan\alpha + N_{lt} - N_{lp} - T_{lp}\tan\alpha - N_{pt} = 0.$$

When the geometry, the masses and the motion are known, the system of six equations allows one to calculate, for example, the driving torques.

Force analysis was performed for a sinusoidal acceleration characteristic according to the equation:

$$a = \frac{\pi v_j}{2T_r}\sin\left(\frac{\pi t}{T_r}\right),$$

which corresponds to the robot velocity shown in Fig. 8.

Typical maximum driving torques needed to bring up robot from standstill to velocity v_j for different times T_r and two roadway inclination angles α are shown in Fig. 9.

The plots of the calculated driving moment needed to realize the assumed motion for travelling on a horizontal surface and on an uphill incline of 10°

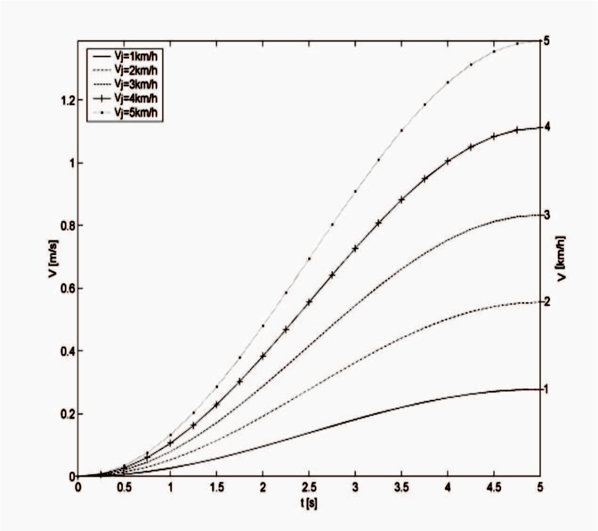

Fig. 8. Assumed characteristic of robot motion

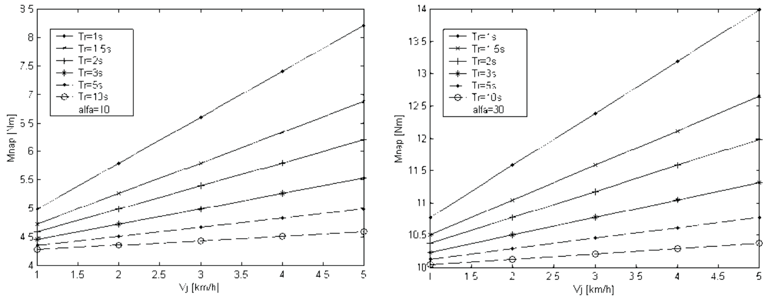

Fig. 9. Maximum driving torques when bringing robot to speed v_j for different acceleration times T_r and different base inclination angles α

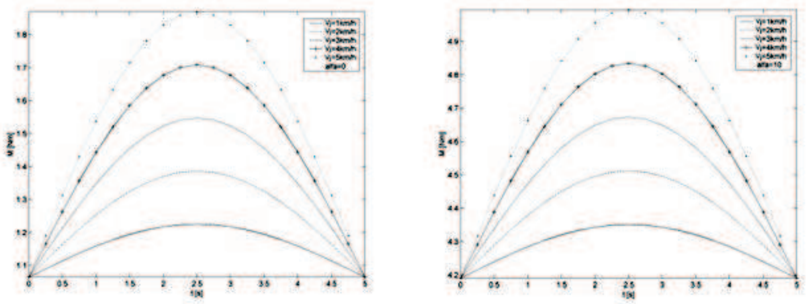

Fig. 10. Driving torque for bringing robot to speed at base inclination of $\alpha = 0°$ and $\alpha = 10°$

are shown in Fig. 10. The above analysis of robot motion shows the theoretical demand for driving torque. To obtain real torques, efficiency of transmission used in driving system must be taken into account. In some cases, it will be impossible to achieve the desired motion (acceleration) characteristic because of the limited value of friction coefficient. This should be taken into account when designing the motion of the robot (the control system) and, for example, the acceleration should be made dependent on the actual base.

4. General idea of control system

The control system is responsible for the operation of the robot and for all its motions and reactions. It is in the control system that computations are performed and suitable decisions are made. The architecture and complexity of the control system depend on the kind of robot and the degree of its complexity (e.g. the number of DOFs, the number and kind of measurement data).

4.1. Description of robot operation

As assumed, the robot will move on wheels, executing the trajectory assigned by the user or an external planning system, while keeping the platform level. Levelling will be performed automatically through changes in the configuration of the limbs to accommodate the terrain irregularities.

The robot's additional function is walking. If the robot encounters an obstacle (a threshold, a kerb, etc.) and cannot get around it, thanks to special suspension systems the robot can negotiate it by walking on it or over it. The obstacle is located by sensors situated in front of the wheels and the whole procedure is carried out automatically.

During its normal operation, the robot moves on wheels and so it has four points of contact with the base but the use of the walking function may result in the loss of stability – when it walks, one of its limbs is raised and the robot loses one of its points of support. As a result, the stability area, determined now by three points of contact, is reduced and so pressure between each wheel and the base should be measured to prevent the centre of robot mass from getting out of triangular stability area. For this purpose, the robot is equipped with a system measuring the pressure exerted by the wheels onto the base. On the basis of the pressure measurement, the robot changes the position of the centre of its mass as well as position of support points by changing the limbs' configuration and in this way it controls its stability.

The general idea of the robot operation is based on the behavioural controller. When the robot receives a task to perform (a motion trajectory), it begins to carry it out. Receiving data from the level sensors (inclinometers) and the obstacle detection system, it automatically adjusts the configuration of the limbs to the uneven terrain and negotiates the obstacles encountered on its way to the destination.

Moreover, during robot operation all the parameters are being visualized and recorded whereby later the functioning of the individual systems can be analyzed and errors detected. From the data one can also draw conclusions about the effectiveness of the control algorithms. In addition, the picture from a camera mounted on the robot is displayed on the user panel.

4.2. Structure of control system

The control of the wheel-legged robot is a complex task. The system has many DOFs and in order to function properly it needs a considerable number of measurement data to be collected and processed and the motion of many drive motors to be synchronized. The control system can be made in different versions, using different available components depending on the needs.

Three main functional modules can be distinguished in the robot control system (Fig. 11). The first module is responsible for levelling (keeping horizontal position of the platform), the second for robot drive on wheels (the wheel drive and turning), and the third for walking. The driving module and the levelling module can work independently from each other, whereas the walking function requires that all the three modules be synchronized. First, the robot should reach the located obstacle, then raise a limb, move it over the obstacle and lower it, and do the same with the other limbs. At the same time the stability of the robot should be ensured during walking.

All the modules can be controlled from the level of central computer to which the local controllers boards are connected. The individual local modules carry out commands coming from the central computer. This applies particularly to executing the motions of the motors to the assigned position or with the assigned speed and to transmitting current measurement data (position, speed). The additional measuring modules supply other data (the base reaction value, the distance from obstacles, the deviation from the level, the supply battery status, etc.) needed for the operation of the robot. All the data from the modules on request are transmitted (via robot internal serial connection net) to the main computer and on this basis the latter generates appropriate responses.

An industrial computer PC 104 was used as the robot's central computer. The unit is based on the LX800 processor with reduced power consumption. It is a fully autonomous small-size computer with sufficient computing power and wireless WLAN transmission. It has four serial communication ports

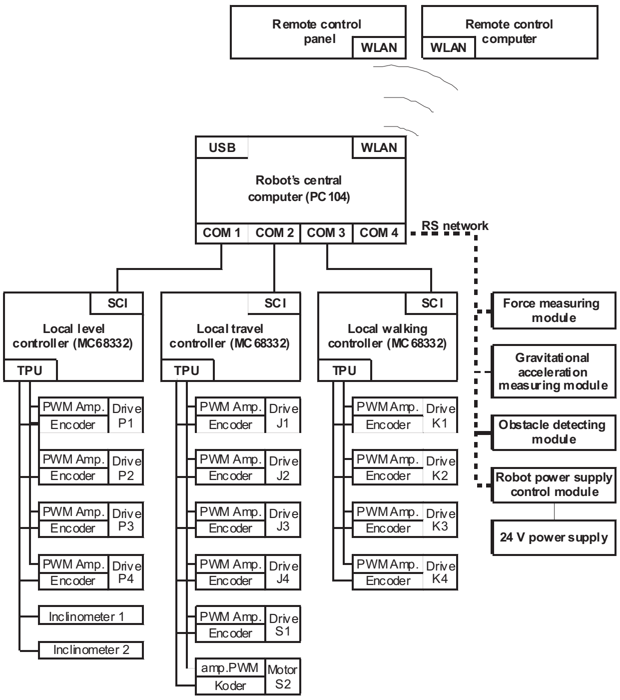

Fig. 11. Structure of robot's control system [12]

RS232 used for communication with the local modules. The (master-slave) communication in the robot is fully controlled by the central computer. Having sent a request to a proper module, the central unit receives a specific amount of data (measurement data, motion parameters acceptance acknowledgement, etc.) dependent on the request sent.

Three of the subordinate microcontrollers, connected to three different ports, are responsible for the motion of the drive motors. Receiving the assigned position (position, walking and turn parameters) or speed (the drive of the robot wheels) the microcontrollers locally attain the assigned values using a PID controller. The adjustment takes place within the microcontroller with position value feedback from encoders mounted on the motor axles. The voltage in the motors is adjusted through changes in the pulse-width modulation (PWM) of the command signal. A full position and speed controller was built on the basis of microcontroller MC68332 [13].

5. Prototype of LegVan wheel-legged robot – experiments

Similarly as any mechatronic device, the wheel-legged robot incorporates a mechanical part, an electronic part and software (responsible for the functioning of the whole). The robot has a modular structure whereby it can be easily modified and expanded by replacing or adding components. The prototype of the LegVan wheel-legged robot is shown in Fig. 12.

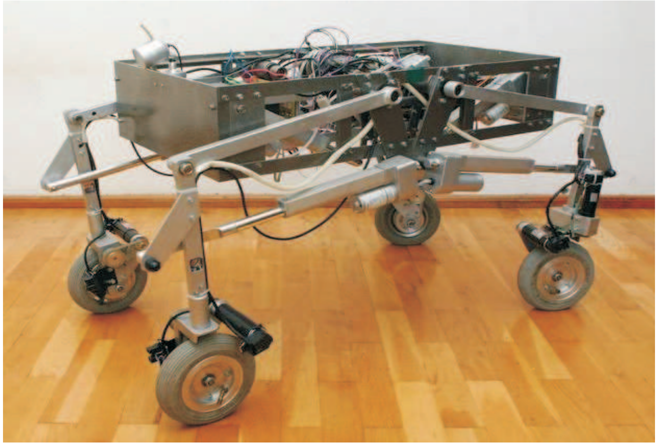

Fig. 12. Prototype of LegVan wheel-legged robot

The robot base is a 750×400×150 mm platform to which four identical limbs are attached. Each of the limbs is connected at two points to the platform.

The limb kinematic system (described earlier) enables an important robot function – the levelling of the platform is performed using only one drive. Each limb ends with a wheel driven by an electric motor, responsible for the motion of the robot. The driving torque is transmitted through a planetary gear and a belt transmission. The robot prototype was subjected to operation tests, particularly its function of levelling in uneven terrain and negotiation of obstacles were tested.

The levelling function was tested on the obstacle course shown in Fig. 13. A series of robot runs at different speeds were carried out.

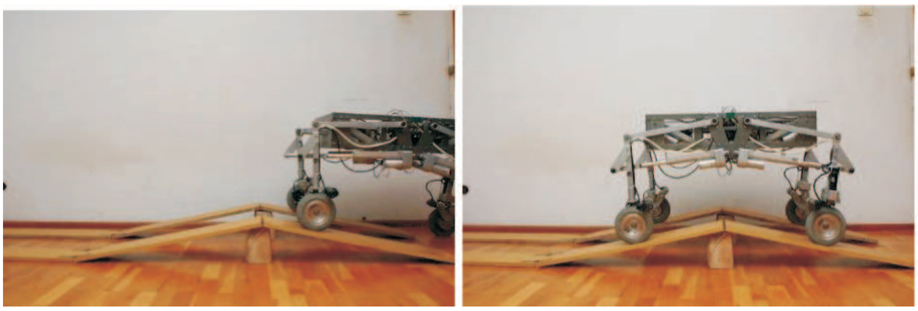

Fig. 13. Obstacle course – levelling function testing

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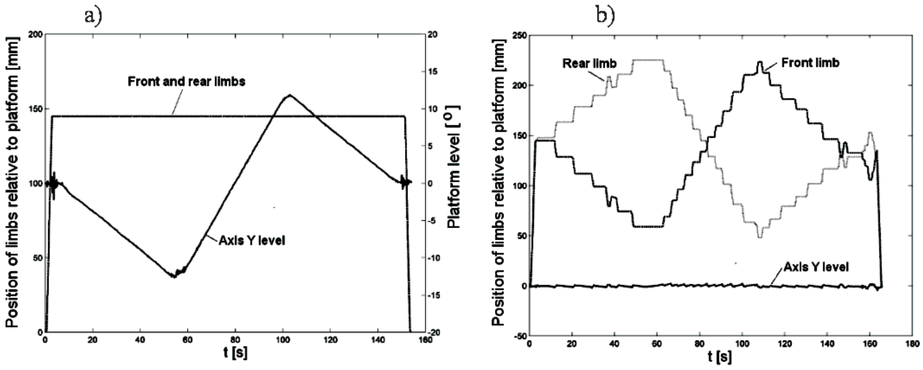

Fig. 14. Measurement data – levelling function turned off (a) and on (b)

For comparison, a robot run with the levelling function turned off was carried out. The measurement data read during the experiment are shown in Fig. 14. When the levelling function is turned off, the reading of the sensor of platform deviation from the level (inclinometer) changes as obstacle course unevenness changes (Fig. 14a). When the levelling is turned on, the unevenness is levelled by the suspension system (Fig. 14b).

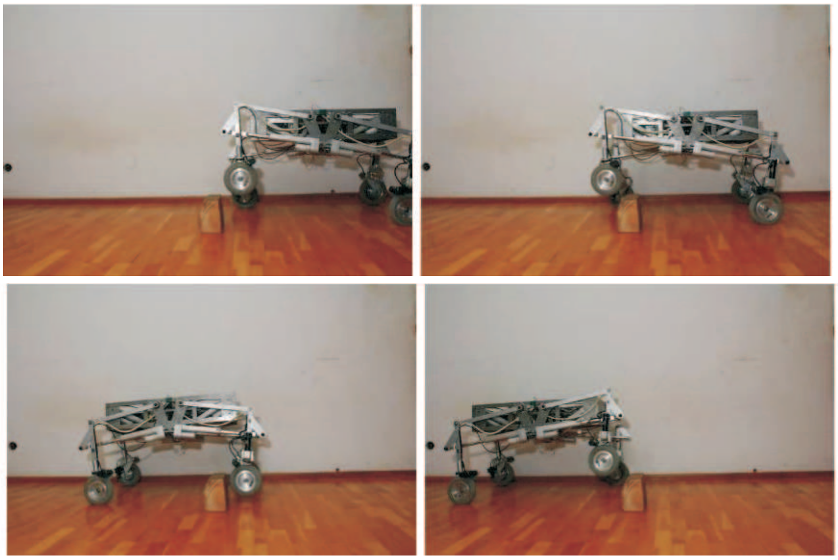

Fig. 15. Walking function testing – obstacle in front of one wheel

The walking function was tested by testing the negotiation of obstacles situated in front of one (Fig. 15) and two (Fig. 16) of the robot's wheels. The walking function is autonomous: receiving data from the distance sensor

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situated in front of the wheel the robot on its own locates the obstacle, determines its height and negotiates it.

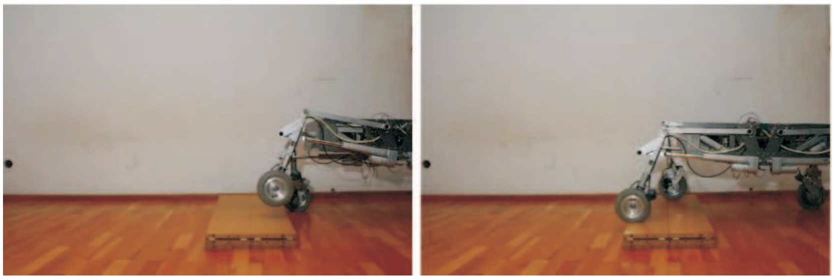

Fig. 16. Testing of walking function – obstacle in front of one wheel

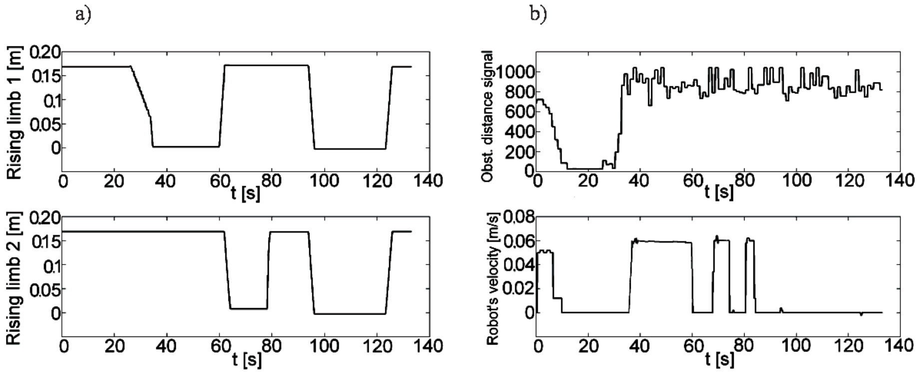

Fig. 17. Measurement data read off robot during walking

The data read off during the performance of the walking function when the obstacle is in front of one of the wheels are shown in Fig. 17. The first of the traces represents the raising of the front limb (1) and the rear limb (2) (Fig. 17a). Figure 17b shows the signal from the distance sensors and the robot's speed. The obstacle is negotiated as a result of carrying out a programmed procedure, whose input parameters include the robot configuration data, the distance to the obstacle and the pressure of the wheels onto the base.

The actual design of the LegVan wheel-legged robot and its testing have proved the research directions taken to be correct. Thanks to the wheel-legged suspension system design it was possible to considerably simplify the control system, particularly as regards the walking function when there is an obstacle in front one of the robot's wheels [15].

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Idea budowy czworonożnego robota kołowo-kroczącego

Streszczenie

Czworonożny robot posiadający zdolność jazdy na kołach, z możliwością poziomowania platformy i jednocześnie dysponujący funkcją kroczenia, wymaga takiego rozwiązania układu kinematycznego kończyn, aby koła dysponowały co najmniej czterema stopniami swobody. Daje to łącznie układ o wielu stopniach swobody i wielu sterowanych napędach. W pracy przedstawiono innowacyjne rozwiązanie, w którym dla głównych faz ruchu robota, tj. jazdy po nierównościach z utrzymywaniem platformy robota w poziomie, dzięki specjalnie dobranej geometrii układu kinematycznego kończyn, zmniejszono liczbę napędów o cztery, które są wykorzystywane tylko w fazach kroczenia. Zaprezentowano budowę robota, wymaganą geometrię członów kończyn oraz określono charakterystyki momentów napędowych. Zarysowano również ideę budowy układu sterowania. W zakończeniu przedstawiono wybrane wyniki badań prototypu robota.