DESIGN AND SIMULATIONS OF WHEEL-LEGGED MOBILE ROBOT

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Abstract: The problems of determining dynamic and kinematic parameters of wheel-legged mobile robot were considered in the paper. The numerical computer model of robot was worked out and simulation researches of suspension were completed. The motion of wheel on road with obstacles and walking motion of wheel were analyzed for determining kinematic and dynamic parameters.

Key words: Mobile Robots, Wheel-Legged Robots, Computer Simulation

1. INTRODUCTION

The demands of today's world, the need for automating transport processes and the necessity of inspecting explosion hazard areas or chemically or biologically contaminated areas necessitate the use of automatic vehicles, i.e. mobile robots (Trojnacki et al., 2008).

Mobile robots have been the subject of research at many (university, military and industrial) research centres. The research covers wheeled robots, walking robots, tracked robots, crawling robots, flying robots, floating robots, and their hybrids. As a result of the research many varieties of such vehicles, differing in their way of travel: wheeled systems (WalkPartner (Halme 2003)), tracked systems (INSPECTOR Robot (Hołdanowicz 2008)), walking systems (PetMan (Boston Dynamics)), floating systems and flying systems (Hermes® 900 (Elbit Systems)), have been created.

The problems investigated in the research centres relate to the design of the particular mechanical assemblies, the control systems and the sensor systems, the modelling of kinematics and dynamics and the potential application of the proposed solutions (Tchoń et al., 2000, Zielińska 2003).

Today vehicles mainly move on wheels. Wheeled solutions are most effective on smooth surfaces in urbanized areas, but their drawback is that they are unable to negotiate obstacles in the form of base discontinuities, such as curbs, stairs and sharp dips.

The commonest form of locomotion of living organism on the surface of the earth is walking. This kind of locomotion is especially effective for moving in unurbanized terrain with an irregular ground with obstacles.

One of the trends in mobile robot design are hybrid wheel-legged robots. Such robots combine efficient travel on wheels in flat terrain with the capability of surmounting obstacles by walking. Owing to its hybrid structure the robot is capable of higher speeds on a suitable base and when it encounters an obstacle which cannot be driven over, the robot moves by walking.

A robot of this kind is being designed and built as part of a research project funded from the financial resources for science (Bałchanowski and Gronowicz 2009). This paper presents the structure of the computational models used and the results of the simulations run. A special focus is on developing an algorithm for robot walking and on simulation studies of robot travel in terrain with obstacles.

2. DESIGN OF WHEEL-LEGGED ROBOT

As part of the project a wheeled-walking robot design, shown schematically in Fig. 1, has been created. When designing the robot a major challenge was to design a wheel suspension system enabling the robot to both move on wheels and walk. The wheel suspension is a complex mechanism with four degrees of freedom relative to the robot's chassis. The mechanism, shown schematically in Fig. 2, must steer the wheel in such a way that it can run (roll and turn – 2 DOF) and walk (be lifted and protruded – 2 DOF) (Bałchanowski 2012, Sperzyński 2010).

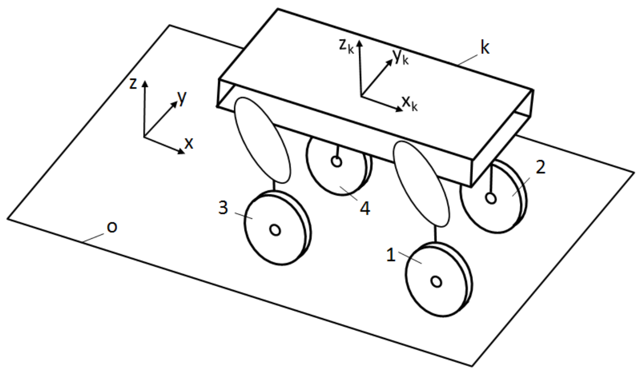


Fig. 1. The general scheme of wheel-legged robot (1 ÷ 4 – wheel suspensions, *o* – ground, *k* – robot's chassis)

As a result of the studies a suspension structure was designed and then its basic dimensions were matched through geometric synthesis (Sperzyński et al., 2010). The fundamental assumption in the design of the suspension structure was that a single drive would effect the particular wheel movements (the lifting, protruding, turning and rolling of the wheel), which would simplify the steering system design and facilitate steering.

The next step was to design the wheel-legged robot structure. It was assumed that the wheels would be symmetrically arranged relative to both the axis of travel and the chassis's lateral axis. This arrangement of the wheels ensures identical travel conditions for going forward and backward. Fig. 3 shows the right side of the robot and a kinematic scheme of suspensions of wheels 1 and 3.

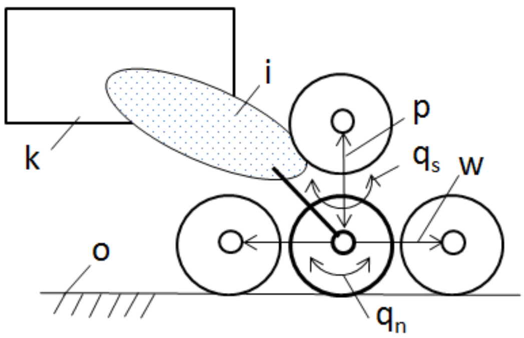


Fig. 2. Schematic diagram of suspension of robot's wheel *i* (*p* – lifting, *w* – protruding, q_n – rolling, q_s – turning)

The robot is designed for inspection work both outdoors and indoors (e.g. in buildings, production halls, etc.). Since it is to move inside rooms, pass through typical doorways (less than 0.9 m wide) and be able to surmount an obstacle with a height equal to that of a typical stair step (the wheel lifting height greater than 0.2 m) its overall dimensions had to be limited.

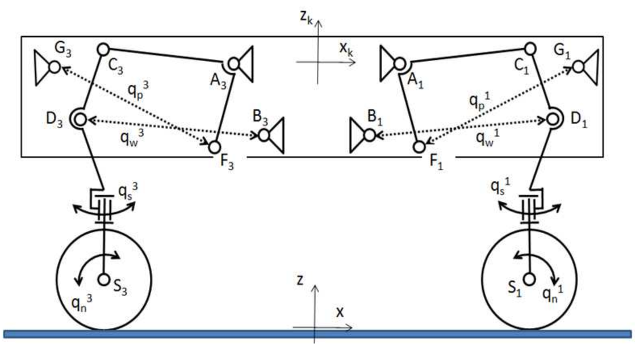


Fig. 3. The kinematic scheme of right side wheel-legged robot (view of suspensions of wheels 1 and 3)

Tab. 1. Main geometrical parameters of wheel *1* suspension

Name	Value	Name	Value	Name	Value
x_{A1}	0.11 m	y_{A1}	-0.65 m	z_{A1}	0 m
x_{B1}	-0.04 m	y_{B1}	-0.65 m	z_{B1}	-0.152 m
x_{G1}	0.518 m	y_{G1}	-0.65 m	z_{G1}	0.005 m
D_1S_1	0.353 m	A_1F_1	0.17 m	A_1C_1	0.303 m
C_1S_1	0.5 m	C_1D_1	0.162 m		

The suspension system's design and basic dimensions are such that the lift and protrusion (walking) motions can be effected by linear drives. i.e. electric actuators LINAK LA36. Solid rubber-steel wheels with a motor and a gear integrated with the hub (GOLDENMOTOR HUB24E) were chosen for the travelling drive. Tab. 1 shows the main geometrical parameters of the suspension of wheel 1. The main specifications of the wheel drives and the lift and protrusion actuators are shown in Tab. 2.

3. COMPUTATIONAL MODEL OF WHEEL-LEGGED ROBOT

In order to carry out simulation studies. a computational model of the robot (Fig. 4) was created in the LMS DADS (Haug1989) system for dynamic analysis. The robot has 22 DOF. each wheel suspension having 4 DOF relative to the body and the latter having 6 DOF relative to the ground.

Tab. 2. Main specifications of drives

Actuator LINAK LA36		
	q_w. q_p (stroke length)	0.35-0.5 m
	v_w. v_p (speed)	0.068 m/s
	F_w. F_p (Force)	1700 N
	m_s (mass)	4.9 kg
Wheel GOLDENMOTOR HUB24		
	dq_n/dt (angular velocity)	13.08 rad/s (125 rpm)
	M_n (nominal Torque)	13.5 Nm
	k_r (radial stiffness)	9.5x10^{5}N/m
	m_k (mass)	5 kg
	r_k (radius of wheel)	0.105 m

Sixteen kinematic excitations: 8 rotational excitations q_n^i and q_s^i (wheel rolling and turning) and 8 linear excitations q_p^i and q_w^i (wheel lifting and protruding). for each suspension *i* (*I = 1÷4*) were defined in the robot.

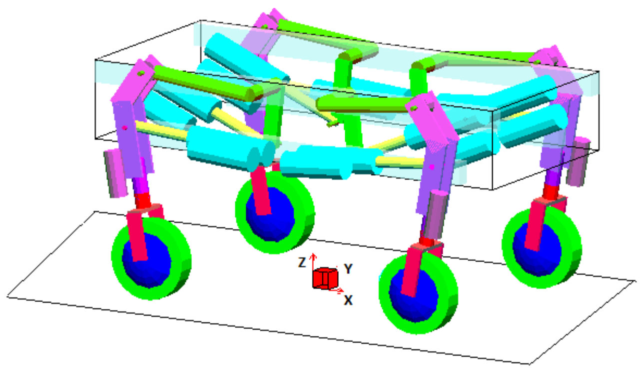


Fig. 4. General view of wheel-legged robot computer model

The wheel/base interactions were modelled using a tyre / ground interaction force model (TIRE). The mass of the wheels is quite large due to the fact that a motor and a gear are incorporated into the hub. and because of their high radial and longitudinal stiffness (Tab. 2).

The total weight (the deadweight + the payload) of the wheeled-legged robot was estimated at 100 kg. The mass and geometry of the suspension. wheel and actuator members were assumed as in the design. The body's weight (comprising the deadweight of the frame bearer. the steering system. the batteries and the current generator. and the payload) was appropriately matched to obtain the robot's assumed total weight of 100 kg. with the centre of gravity located in the body's centre.

4. SIMULATIONS OF WHEEL-LEGGED ROBOT

Computer simulations are run in order to study the behaviour of a system while it performs the working motions and to determine the main kinematic and dynamic parameters. Through computer simulations one can determine the validity of the structure being created when the latter is at a virtual prototype stage.

As part of this research the travelling of the robot on a ground with an obstacle was studied. The dimensions of the obstacle placed on the track are such that the obstacle has to be surmounted by walking. Walking becomes necessary when the obstacle's height h_p is larger than the wheel's radius r_k.

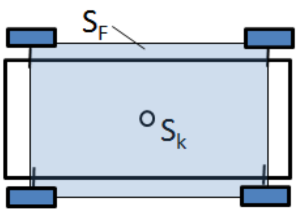


Fig. 5a. Robot stability field S_F for four-wheel support

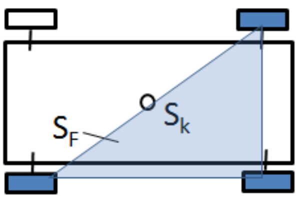


Fig. 5b. Robot stability field S_F for three-wheel support

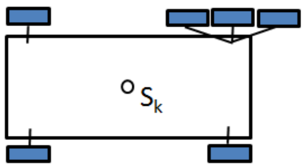


Fig. 5c. Examples of wheel position change effected by changing settings of protrusion actuator q_p

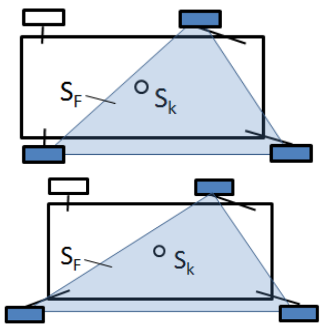


Fig. 5d. Robot stability field S_F for three-wheel support for two wheel protrusion

When performing the walking motion the wheel is lifted by lift actuator q_p and moved into a position above the obstacle by protrusion actuator q_w. During this motion the wheel loses contact with the base. as a result of which the number of the robot's points of support changes from four to three whereby the shape of the system's stability field S_F changes.

When robot rests on its four wheels the system's stability field S_F is quadrangular with gravity centre S_k (Fig. 5a) lying in the centre of the quadrangle. When one of the wheels is lifted. the robot's stability field S_F is triangular with gravity centre S_k situated on the stability boundary (Fig. 5b). This position does not ensure the system's stability during walking and the robot may overturn. In order to ensure the operation of the system is stable one should change the locations of the robot's points of support to enlarge stability zone S_F. This can be achieved through protrusion motions q_p^i of individual wheels *i* (Fig. 5c). The possibilities of changing the area of stability zone S_F when wheel *4* is lifted are shown in Fig. 5d.

The fundamental problem in negotiating an obstacle by walking is to program the walking in such a way that when the successive wheels are lifted in the course of surmounting the obstacle the stability of the robot is always ensured.

The lifting of the chassis relative to the ground is used to adjust the body's working elevation h_k relative to the ground during robot travel. i.e. to adjust the clearance under the robot. The clearance is usually set before travel. For travelling at the maximum speed the robot's clearance is set to minimum (h_k^{min} = 0.3 m) whereby the system's centre of gravity is situated low (as shown in Fig. 6). For travelling in terrain with obstacles the chassis is maximally lifted (h_k^{max} = 0.52 m). The nominal working chassis elevation setting is h_k = 0.41 m. Lifting height h_k is effected by lift actuator q_p.

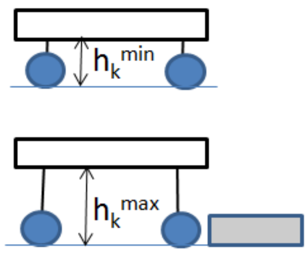


Fig. 6. View of robot for two variants of body position above base

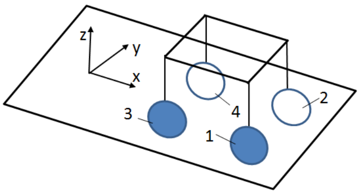
Wheel separation from the ground is effected by lift actuator q_p^i which lifts one of the wheels while the position of the other three wheels remains fixed. The robot can lift the wheel to height h_S=0.25 m. This height can be achieved only at the maximum body elevation. The obstacle to be negotiated by the robot cannot be higher than 0.25 m.

The obstacle negotiation procedure consists of many stages which can be summarized in the form of the following algorithm:

1. the robot's front wheels move up to the obstacle.
2. the robot's chassis is maximally lifted.
3. the stability field is set for wheel 1 to be lifted.
4. wheel 1 is lifted and moved into a position above the obstacle.
5. the stability field is set for wheel 2 to be lifted.
6. wheel 2 is lifted and moved into a position above the obstacle.
7. the robot's rear wheels move up to the obstacle.
8. the stability field is set for wheel 3 to be lifted.
9. wheel 3 is lifted and moved into a position above the obstacle.
10. the stability field is set for wheel 4 to be lifted.
11. wheel 4 is lifted and moved into a position above the obstacle.
12. the stability field is set for the four-wheel support.
13. the body is set to the working elevation.

The particular stages in walking over an obstacle are shown in Figs 7a and 7b.

The following were simulated: the approach of the robot to an obstacle with height h_p = 0.15 m and length l_p = 2 m. its ascent of the obstacle by walking. its drive on the obstacle and rapid descend (without walking) from it. A schematic of the simulation is shown in Fig. 8. The total motion time is t = 24 s. The robot approaches the obstacle and drives on it at body speed v_k = 1m/s.



Rys. 7a. Schematic diagram of wheel-legged robot (blue wheels right side. white wheels left side)

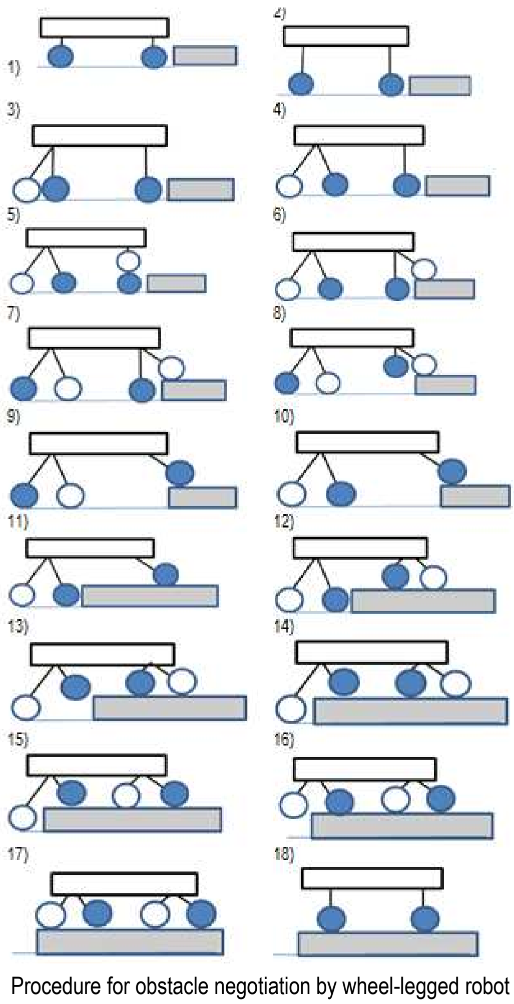


Fig. 7b. Procedure for obstacle negotiation by wheel-legged robot

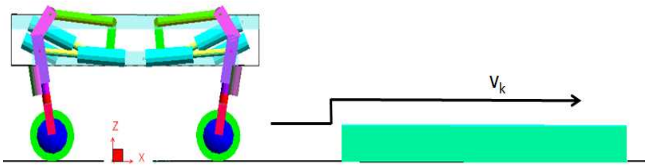


Fig. 8. Schematic of simulation of robot travel on base with obstacles

Figs. 9-16 show the results of the computations. Fig. 9 shows the changes in the location of robot's chassis centre S_k (coordinates *x. z*). The diagrams in Fig. 10 show the changes in the height of the centres of the robot's (the left side) wheels *1* and *3* during its motion. One can clearly distinguish the particular stages in robot travel: t = 0-2.0 s – the approach to the obstacle. t = 3.0 s – the beginning of walking. t = 16.0 s – the end of walking (the robot is on the obstacle). t = 16.0-18.9 s – the drive on the obstacle. t = 18.9 s – the front wheels begin to fall from the obstacle. t = 22.12 s – the rear wheels begin to fall from the obstacle.

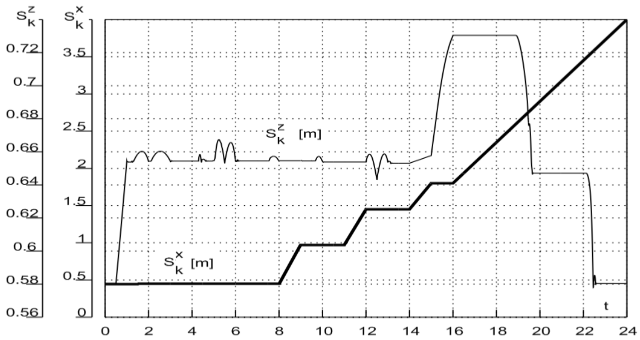


Fig. 9. Changes in location S_k^x. S_k^z of robot's chassis centre during robot travel

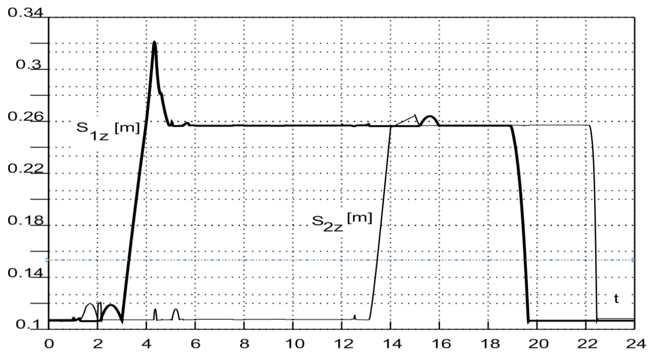


Fig. 10. Changes in height S_1^z. S_3^z of centres of wheels *1* and *3*

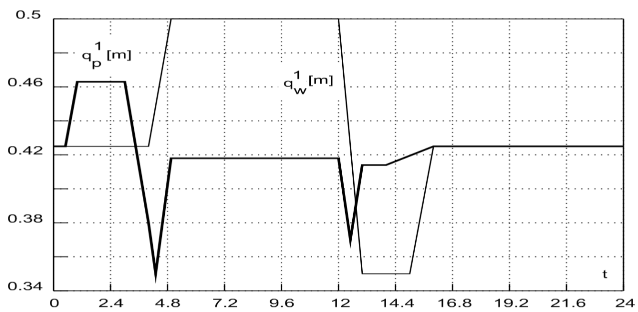


Fig. 11. Diagrams of lift q_p^1 and protrusion q_w^1 excitations for (front right) suspension *1*

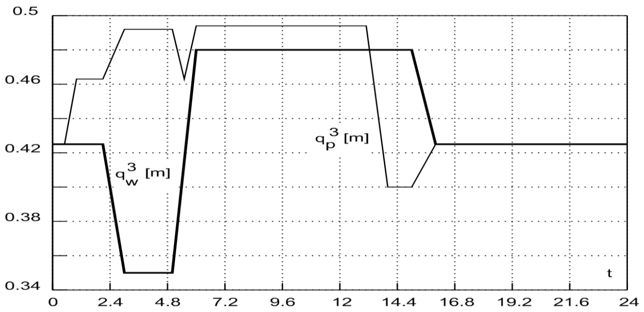


Fig. 12. Diagrams of lift q_p^3 and protrusion q_w^3 excitations for (rear right) suspension *3*

The changes in lift excitations q_p and protrusion excitations q_w for suspensions *1* and *3* (the robot's right side) are shown in Figs. 11 and 12. The excitations are responsible for the performance of the particular walking stages according to the algorithm shown in Fig. 7. Active lifting forces F_p and active protrusion forces F_w for (front left) suspension *2* are shown in Figs. 13 and 14.

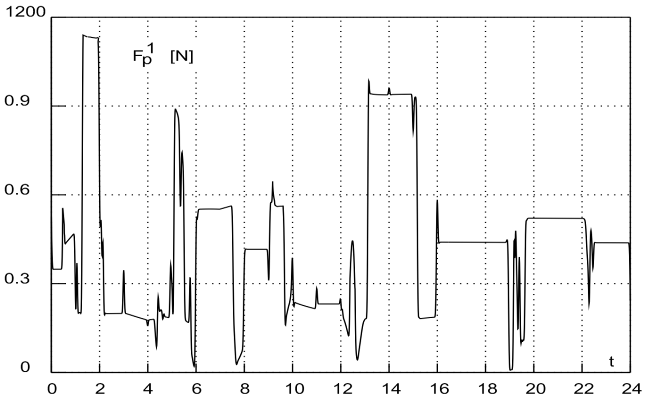


Fig. 13. Diagram of active force F_p^1 in lift actuator in (front right) suspension *1*

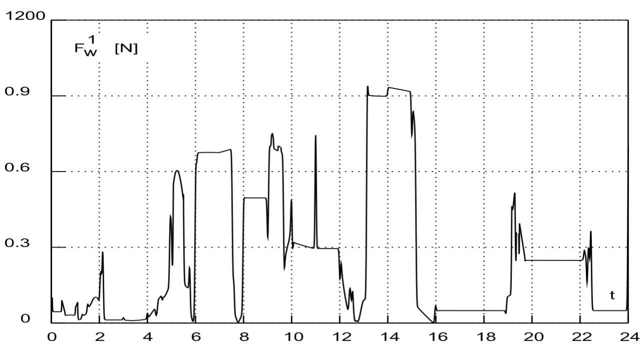


Fig. 14. Diagram of active force F_w^1 in protrusion actuator in (front right) suspension *1*

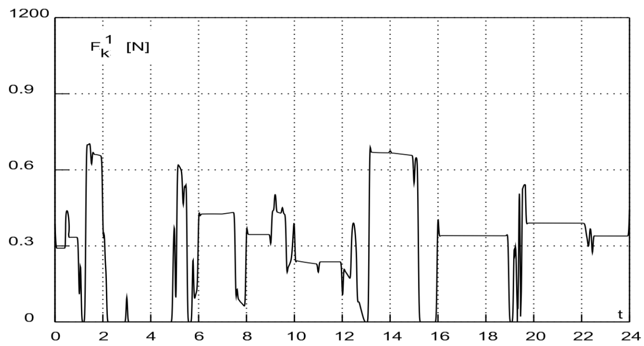


Fig. 15. Diagram of (front left) wheel *1* and base interaction forces F_k^1

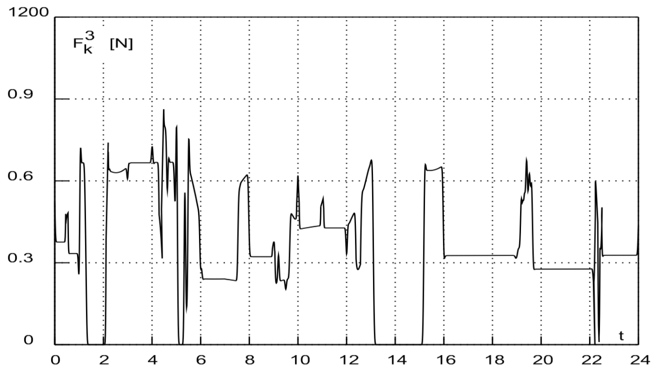


Fig. 16. Diagram of (rear right) wheel *3* and base interaction forces F_k^3

Figs. 15 and 16 show the diagrams of interaction forces F_k in the contact of wheels *1* and *3* with the base. Also in these diagrams the character of the changes in the wheel travel phases is clearly visible. In the force diagrams (for time t = 2.0-16.0 s) when examining the wheel/base contact loss instants one can distinguish the particular walking stages.

The last stage of motion (for t > 18.9 s) illustrates the results of a numerical experiment simulating the travel of the robot on a ground with a sharp dip negotiated without walking. The moment when the front wheels (shortly followed by the rear wheels) fall from the obstacle is particularly distinct (Fig. 10). The lift and protrusion actuators are particularly heavily loaded in this phase (Figs. 13 and 14).

The simulation results presented here are only a sample selected from the results of the numerous studies which have been carried out. A detailed analysis of the robot loads needs to be made in order to select proper drives and to do structural calculations. As it appears from Tab. 2. the electric drives LINAK LA36 adopted for lifting and protruding meet the dynamic requirements since driving forces F_w and F_p (Figs. 13 and 14) do not exceed the nominal forces specified by the manufacturer. even during the negotiation of extreme obstacles.

5. CONCLUSIONS

The creation of a computational model and simulation studies of a wheeled-walking robot have been described. Robots of this kind are complex mechanisms subjected to considerable variable loads resulting from travel on a ground with obstacles. The identification of the state of load in the robot is an essential step in building an efficient and reliable robot system.

For the robot considered here a computational model was created using a computer system for dynamic analysis. A procedure for robot walking aimed to overcome an obstacle appearing on the track was developed. The walking procedure takes into account a change in the stability field. resulting from a change in the way the robot is supported while the wheels are being lifted and from the adjustment of the field to ensure the stability of the system.

The robot structure was evaluated and its performance verified through simulations of driving and walking and an analysis of the obtained results for one chosen procedure for obstacle negotiation. The adopted design can be the basis for the construction of a wheeled-walking robot.

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