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# THE STABILIZATION OF THE POSITION OF THE BODY OF WALKING MACHINES

A. P. BESSONOV and N. V. UMNOV
Institute for the Study of Machines, Moscow, U.S.S.R.

**Abstract**—This paper shows that in the task of the maintenance of constant orientation of the body of a walking robot the determination of the actual position of the body, i.e. absolute altitudes of its points and remoteness from the supporting surface, is the most complicated problem. Two possible systems of measurement and stabilization of the position by the height of the body of the walking mechanism are compared, i.e. a system of adaptation automatically adjusting the length of the supporting leg to the roughness of the terrain, and the system of the maintenance of constant remoteness of the body from the terrain. The inefficiency of a solitary application of any described system is revealed and the possibility of an accumulation of errors of the position of the body by the walking on the soft terrain is shown. Possible approaches for raising the quality of stabilization of the body by the walking are evaluated.

A walking device supplied with orthogonal propelling agents (Fig. 1) automatically supports the invariable absolute height of the body owing to the principle of its work. This occurs because each leg is supplied with a touching sensor which switches off the drive of vertical displacement of the leg after touching the terrain by the leg and switches on a locking device fixing a given length the leg can be pulled out.

This system of adaptation[1] suggests that in the moment of lowering the next leg the body stands on the other legs steadily maintaining its horizontal position which is not shifted after standing and fixing the leg.

The insufficiency of this system to adapt becomes obvious during the walking on the terrain if it has a general change of its medium level, for example, while walking on the long slope or on the stairs of the building. Working in these conditions the system of adaptation will bring a gradual decrease of the pulling out of the legs.

Of course, having an operator or driver on board the walking machine, one can impose upon him the duty of correcting considerable errors of the height of the body. In the case described, by the way, it is sufficient from time to time to simultaneously pull out all legs to some degree, i.e. to increase the clearance of the machine. However, in automatic robototechnical devices such a case is impossible.

If the automatic device replaces the driver in this part of his functions, a special system of control which maintains within safety boundaries the amount of remoteness of the body of the machine from the supporting surface is required. The well-known walking machine by Chebyshev[2] and similar ones are free from this deficiency. One can say that the system of automatic maintenance of permanent distance of the body from the supporting surface with the aid of pulling out the legs for the permanent length has been realized. However, the robot with such a system is not efficient as the position of its body when walking on the rough terrain is indefinite. Actually the system has no adaptation.

It is interesting to note that rocking the body of such a walking machine when it is walking on the rough terrain will be more than the rocking of a wheel carriage without springs. In Fig. 2 vertical oscillations of the centre of gravitation of a four-legged walking machine without adaptation overcoming a solitary roughness of a single height on which the carriage steps only by one (right front) leg are shown. The body of the wheel carriage overcoming the same obstacle would have had only two liftings corresponding to the driving on to the obstacle by a front and rear wheels.

Thus, the walking machine without adaptation moves very unevenly and cannot be a chassis-carrier of the robot technical device. It is the system of adaptation that gives to a walking propelling agent characteristics of ideal comfort which cannot be achieved with other types of propelling agents. However, the system of adaptation itself does not ensure safe motion. It is necessary to have both systems which brings us to the task of the differentiation of their functions since their aims are contradictory. The following sequence of acting of both systems seems to be the most natural: the legs adapt to the roughness of the terrain till full contact with all supporting legs and then the length of all supporting legs simultaneously changes in a way that the body would be located at the required distance from the supporting surface. The natural question which may arise is: how does one evaluate the distance from the body to the surface? It would be simple to evaluate it by measuring the distance from any point of the body to the surface with the aid of either locator means or different feelers or other devices of this kind. With an orthogonal scheme of the propelling agent one of the legs may also serve as a measuring element of remoteness of the body from the surface.

The system with the location in one point, even if we ignore the lack of coincidence of the profilegrams of roughness of the terrain under the locator and under the supporting points, has the deficiency of "following" fully the heights of roughnesses, i.e. the

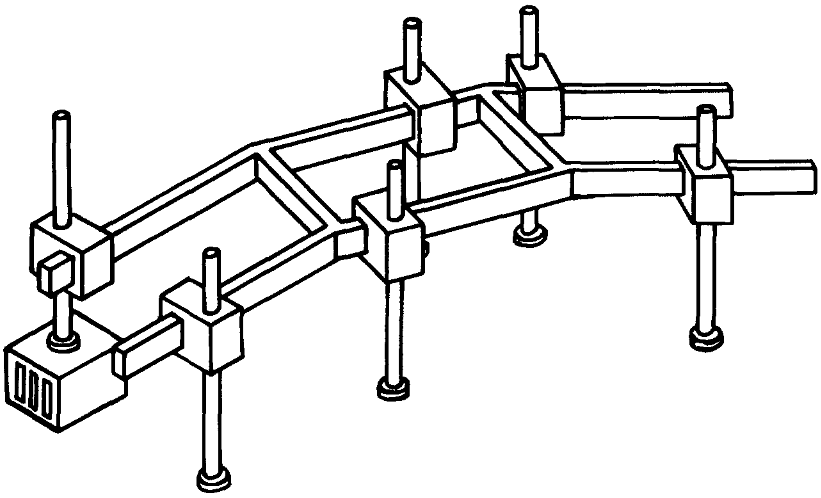

Fig. 1.

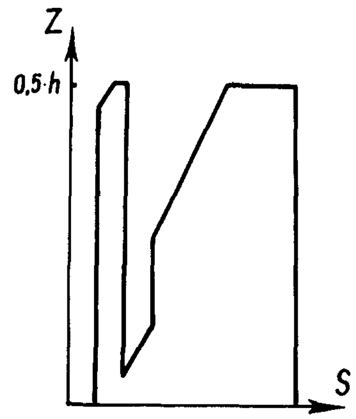


Fig. 2.

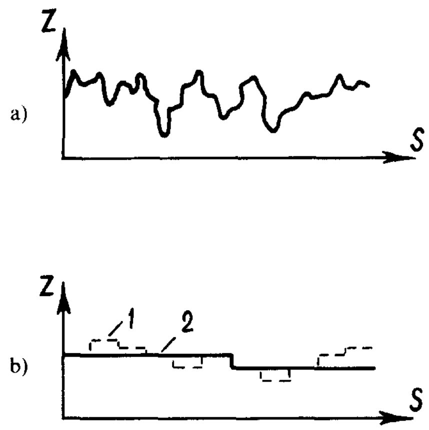


Fig. 3.

body of the machine will have added vertical displacements in its horizontal motion. Thus, the useful effect of ideal comfort of the walking machine is fully destroyed.

Some improvement of comfort can be achieved if we replace the continuous following of the height of roughnesses by the discrete following, accomplished at some intervals of time. In Fig. 3(a) the profilegram of the path is shown. The centre of the body will have the same path at the continuous following. In Fig. 3(b) the path (line 1) of the body at the discrete following while walking on the same roughnesses is given. The interval of discreteness, i.e. the moments of comparison of the height and the following, in this case coincides with the moments of the standing of the legs.

With the increase of the interval of discreteness the comfort grows (line 2 Fig. 3b), though simultaneously the danger grows that the height of the terrain in the point of measurement will not characterize the medium roughness of the terrain.

This danger results mainly from the fact that the measurement of remoteness of the body from the surface is carried out in one point. It can be decreased if we carry out measurements simultaneously in several points. This is especially convenient to perform in machines with an orthogonal walking propelling agent in which the vertical leg with a rack allows easy measurement of the actual pulling out of the leg and thus to measure the distance from the point of its suspension bracket to the surface.

Then it is necessary from the set of $N$ measurements, where $N$ is the number of supporting legs, to form an integral criterion which will characterize the medium remoteness of the body from the surface. It is clear that the comfort of walking and the complication of control will depend on this kind of criterion. Let us assume an arithmetical mean sum of the lengths of pulling out all $N$ supporting legs as a measure of the average remoteness of the body. It should be noted that this value may be easily formed in the walking machine: for this aim a summator of the lengths of pulling out, for example, with summarizing differentials, and a counter of the quantity of supporting legs are required.

The choice of the arithmetical mean sum as a measure has been based on some integral characteristics of sums generally, i.e. on a certain smoothing out effect. For example, in overcoming the obstacle "step"-type of height $h$ (Fig. 4a) by $N$-legged vehicle the body sinks by the height $h$ not at once but gradually, in $N$ steps (Fig. 4b), i.e. peculiar "integration" of the profilegram of the path will occur, which on the whole will favourably result in comfort of the motion.

However, such will be the case only if at each step the next leg steps on to the obstacle. But in normal walking, for example, a six-legged vehicle covers the path, equalling the length of the body, approximately in three cycles of walking which corresponds to 15–18 steps. That is why, except six transfers of legs from one level to another in walking, there will be approximately the same number of "mark time" of the leg on each level. It is natural that it requires 2 or 3 steps on the previous level for the leg, most remote from the edge of the obstacle, before it comes up to the edge of the obstacle and stands on a new level.

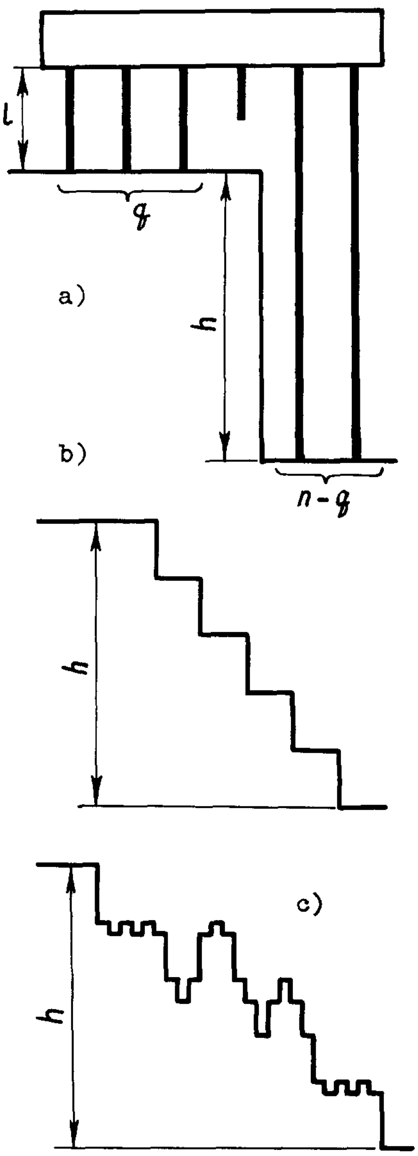

Fig. 4

If in overcoming the step in the intermediate position (Fig. 4a) $q$ legs are yet on the high side and have length $l$ and the rest ($n$-$q$) of the supporting legs are already on the lower side and owing to the work of the system of adaptation have length $(l + h)$, the summary length of all supporting legs equals

$$\sum = Nl + (N - q)h.$$

The arithmetical mean sum $\sigma = \Sigma/N$ will be

$$\sigma = l + \frac{N - q}{N} h.$$

At the lifting of one leg on the high side the summary length decreases by $l$, i.e. it becomes equal to

$$\sum\nolimits_1 = (N - 1)l + (N - q)h$$

and their arithmetical mean calculated in this case by $\sigma_1 = \Sigma_1/N - 1$ will be

$$\sigma_1 = l + \frac{N - q}{N - 1} h.$$

A comparison of $\sigma$ and $\sigma_1$ shows that in this case the body will "squat" by

$$\Delta_1 = \sigma_1 - \sigma \quad \Delta_1 = h\frac{N - q}{N(N - 1)}$$

When the leg is stood back on the high side the return of the body to the previous height, i.e. the lifting by $\Delta_1$, will occur. However, if on the high side an additional leg besides $q$ and generally besides $N$ is mounted, for example, a leg, which at the moment of consideration was at the phase of transfer, then the body will lift by another value $\Delta_2$ as $\Delta_2$ is negative and equals

$$\Delta_2 = -\frac{N - q}{N(N + 1)}.$$

Also, at the lifting of one leg on the lower side, the lifting of the body has value $\Delta_3$ as $\Delta_3 = -hq/N(N - 1)$ and in standing it back to the lower side, the return of the body will occur, i.e. the lowering of it by $\Delta_3$ and at the standing on the lower side of $(N + 1)$st leg "squatting" of the body will equal $\Delta_4 = h(q/N(N + 1))$. Finally, only the lifting of the leg on the high side and the standing of it on the lower one will bring to the squatting of the body value $\Delta_5 = h/N$.

The displacements of the body at the passage depend on the order of the lifting and lowering of the legs, i.e. on the gait. Each one follows its own path of overcoming the obstacle of the same type; however, it is impossible to give any recommendations of choosing the gait owing to the lack of real criterion for their selection. In Fig. 4(b), as an example, we can see the path of the center of the body of the six-legged vehicle in overcoming the step shown in Fig. 4(a), and the parameters of walking were accepted as ($\gamma = \frac{9}{12}$ and $\Delta = 4$). One can see that it differs considerably from the idealized one. The described system—as well as the earlier system—with continuous measurement of remoteness in principle can oppose the slipping down of the body of the robot. It should be understood in the sense that the error in the location of the body caused by the elasticity of its legs and the plasticity of the terrain will be registered and the error in the accumulation of it until the emergency limits can be automatically compensated by the general lifting of the whole body.

However, more detailed study shows that in a pure form the system of keeping the permanent remoteness together with the system of adaptation does not guarantee the full security of walking.

Let us consider one of the simplest forms of slipping down. We shall take an eight-legged vehicle moving by "fours"; the legs mounted on one side and the legs mounted on the other side moving simultaneously. All this gives us the grounds to consider the model.

The model of the leg is one consisting of a hard pivot transferred to the body and located at the end of its elasticity. The leg is weightless; the whole mass is concentrated in the geometrical center of the body. The regime of the leg's work is equal to $\gamma - = 0.5$ (time of the phase of support equals the time of the phase of transfer) and the shift between the work of the fours is also accepted as 0.5 of the cycle of work. In Fig. 5(a) the critical position of such a model, i.e. the moment of changing the supporting fours, is shown. In Fig. 5(a) the body is standing on the rear fours; owing to the different load of the legs, deformations in the supports will not be identical; all this brings distortion of the body. Fig. 5(b) shows the moment of lowering the front fours and fixing the legs relative to the body. As the body stands steadily on the rear fours, the legs are fixed in an unloaded state and the different length of fixation occurs owing to the distortion of the body. After lifting the rear fours (Fig. 5(c) the weight of the body will be on the front fours. The different load of the supports and the inequality of their deformation also distort the body and this slightly corrects the initial distortion Fig. 5(a) though the length of pulling out the legs has become shorter.

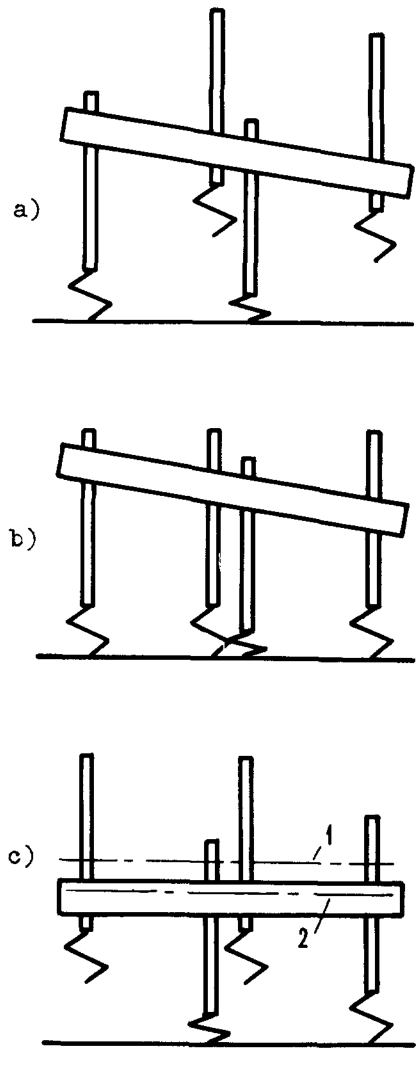


Fig. 5.

The general case for this vehicle is that at the length of pulling out rear and frontlegs, accordingly $l_r$ and $l_f$, and at the availability of the deflection under the load in the moment of the change of the state equals to $\delta$. After changing the state the legs become shorter, the rear one by $l_r - l_f + \delta$ and the front one by $l_r - l_f + 2\delta$. It also results from this that at each change of the state, i.e. at each step of the fours the front end of the body sinks corresponding to the rear one by the value $\delta$. In other words there is still slipping down (climb).

Unfortunately, this latter kind of slipping down is not detected and not corrected by the described systems of maintaining the permanent remoteness of the body of the vehicle. Thus, the system comparing arithmetical mean sums of the lengths of pulling out the legs will show that the initial value $\sigma_0 = \frac{1}{2}(l_f + l_r)$ (in position Fig. 5(a) decreases after changing the state (Fig. 5(c) by the value $l_r - l_f + \frac{3}{2}\delta$ and this will require proper correction of the clearance of the vehicle as shown in Fig. 5(c) by the stroke dotted line 2. The system evaluating the height of the body by the length of pulling out the legs, for example, the rear leg, will also show the slipping down of the body, but in this case by small value $l_r - l_f + \delta$, since in this system the shortening of the other legs is not considered 1. That is why the angular distortion of the position of the body will accumulate at further walking and the possibility of the robot turning over, and ceasing to function will increase.

In conclusion, besides the described systems of adaptation, the walking robot requires the availability of the system measuring and correcting the angular position of its body.

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LA STABILISATION DE LA POSITION DU CORPS D'UNE MACHINE MARCHANTE

A.P. Bessonov, N.V. Umnov

Résumé - On voit que dans la tâche de maintenir l'orientation constante d'un corps d'un robot marchant, la détermination de la position exacte du corps - c'est-à-dire, les altitudes absolues de ses points et l'éloignement de la súrface appuyante - est un problème compliqué. Deux systèmes possibles du mesurage et de la stabilisation de la position par la hauteur du corps du mécanisme marchant sont comparés - à savoir, le système de l'adaptation par ajustement automatique de la longueur de la jambe appuyante à l'inégalité du terrain et le système pour maintenir l'éloignement constant du corps du terrain. L'insuffisance de l'application seule de n'importe quel système décrit est mentionnée, et la possibilité de l'accumulation d'erreurs de la position du corps pour avancer sur un terrain mou est démontrée. Quelques méthodes possibles pour augmenter la qualité de la stabilisation du corps pendant le mouvement d'avance sont évaluées.