INTERLEVEL COOPERATION OF THE WALKER CONTROL ALGORITHM

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Due to its ability of adaptation to the terrain, the walking locomotion system is able, in principle, to provide a higher degree of rough terrain capability along with a higher degree of comfort than provided by wheeled or caterpillar type vehicles. The advantages of the walking systems have been evident for a long time, but there are some difficulties in the development of the walker concept. One of them is the control problem. Stability of the walker and coordination of its legs must be provided when walking over rough terrain. The control problem is expecially difficult in the case when the vehicle has to overcome some obstacles. To solve this intricate control problem the vehicle must be rather "clever".

The natural way is to use a small-size onboard computer and to design appropriate software-control algorithms.

An effective method of testing the algorithms is their simulation on a digital computer with a display unit. By observing on the cathode ray tube the moving image of the vehicle walking over the terrain, it is possible to check the functioning of the algorithms, to estimate their effectiveness, and to find ways for their improvement.

This paper deals with the algorithms in the range from the environment information (input) to the vehicle kinematics (output). The problem of processing the terrain measurement data was not investigated. It was assumed that all necessary information about terrain was kept in the computer memory in a form convenient for its use in the decision-making algorithms.

Some types of six-legged walking systems were investigated. A schematic image of one of them is seen in Figure 1. All six legs of the walker have equal geometric parameters and equal orientation of the joint axes. Each leg has three degrees of freedom in the joints: two in the hip joint and one in the knee. The first hip-joint axis is perpendicular to the plane of the vehicle body, while the second one is parallel to the body plane and perpendicular to the thigh. The knee axis is parallel to the second hip-joint axis. The total number of degrees of freedom in six legs amounts to eighteen. The vehicle body has no kinematic constraints, and therefore it may have six degrees of freedom in its motion relative to the supporting surface.

The walker of this type has rather rich kinematic feasibilities which may be used to provide adaptivity to the terrain. The problem is to synthesize appropriate control algorithms which could organize the kinematics in a reasonable way for the effective solution of different locomotion tasks.

It was resonable to design control algorithms as a multilevel hierarchical system. The following five levels were adopted:

1. *Leg*. This level is the lowest one. It is necessary to synthesize leg motion during the support and swing phases and to avoid small-size obstacles.

2. *Leg coordination*. The leg-coordination algorithms provide support scheduling of the legs, i.e. they generate sequences of "up" and "down" times for all legs. The stability margin of the vehicle should be always no less than a given value.

3. *Standpoint sequence*. This level fixes in advance several supporting points on the support surface. In a simple case, if the terrain relief allows it, then the level generates a regular standpoint sequence described by two parameters: the gauge width and the stride length. In more complicated cases it is necessary to plan an irregular standpoint sequence, e.g. for some cases of climbing over obstacles.

4. *Body* The outpur of this level is the parameters of motion of the walker´s centre of mass both along the route and in the vertical direction, and the parameters of body rotation (pitch, jaw, roll).

5. *Route*.The route planning level is the highest one. Up to now the route of the walker was planned by only one operator.

Figure 2 shows interlevel information flow. The complex of control algorithms is dash-lined. Dotted lines indicate the flow of terrain information to different levels.

It is resonable to begin designing the algorithms from lower levels and then pass on to the higher ones. When testing the algorithms the output of higher levels were simulated.

The initial stage of investigation dealt with the leg-control algorithm in the simple case of regular gait of the walker moving along the regular standpoint sequence; the body moved with

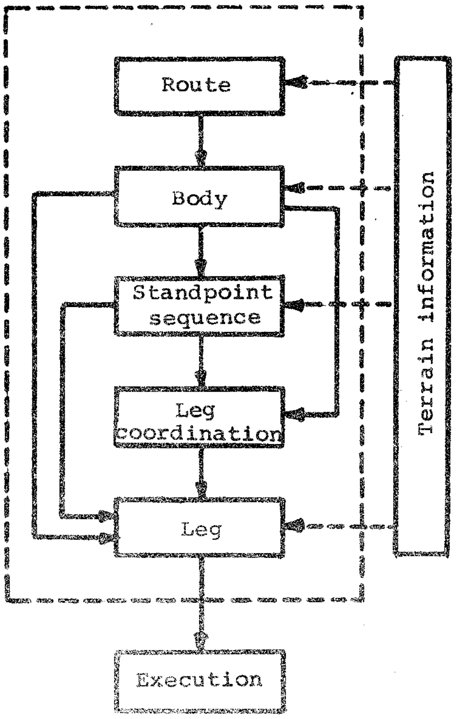

Fig. 2. Information flow in the control algorithm.

[illegible] velocity. The simulation of the levels higher than the [illegible] level was rather simple in this case. The leg-control [illegible] provided vertical legs adaptation to small-scale terrain [illegible]

[illegible] al block was designed for synthesizing leg-tip motion [illegible] swing phase to provide for complicated small-scale re[illegible] [illegible] eded. The ordinates of the leg-tip trajectory (Fig. [illegible] [illegible] lated as the sum of the ordinates of the convex [illegible] [illegible] relief (dashed line in Fig. 3) and of the ordinates [illegible] with a vertical axis. The parabola was chosen in [illegible] at its ordinates were equal to zero both in the ini- [illegible] al points. It was assumed that the horizontal compo- [illegible] leg-tip velocity was constant during the entire swing [illegible]

[illegible] second level, leg coordination, the algorithm for

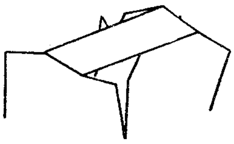

Fig. 1. Schematic image of six-legged walker.

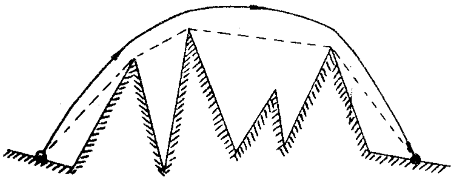

Fig. 3. Leg-tip trajectory in case of complicated relief.

support scheduling with prescribed stability margin was designed in a general case for irregular standpoint sequence.

Two types of gait were investigated:

1. *Tripod gait.* Each of the two tripods consists of foreleg and hind leg of one side and of middle leg of the other side. Three legs of the tripod swing simultaneously. Two tripods swing alternately. Figure 4a illustrates the adopted logics of calculating "up" and "down" times of the tripod in the case when all legs on the same side use the same standpoint sequence ("step-in-step" type of locomotion). The swing phase of the tripod coincides with the time interval when the projection of the centre of mass of the walker moves between two dashed lines inside the supporting triangle formed by the legs of the other tripod (Fig. 4a). This logic provides stability margin of a prescribed value.

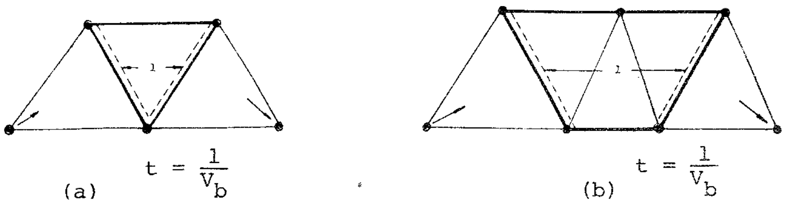

Fig. 4. Support scheduling logic
(a) tripod gait
(b) wave gait.

2. *Wave gait.* The idea of this type of gait was taken from one of the enthomological papers by D. Wilson. The swing waves

propagate along the legs of each side of the walker beginning from the hind legs. The hind legs on both sides start alternately.

Support scheduling logic is shown in Figure 4b. The time interval between the start of the hind leg and the standing of the foreleg (wave propagation time) was calculated under a condition of prescribed stability margin. Two equal intervals of simultaneous support of hind and middle legs, and of middle and front legs were subracted from the wave propagation time. The rest of the time was divided among three legs proportional to their strides (the rule of constant leg-tip horizontal velocity).

It should be noted that in special case of regular standpoint sequence the gaits generated both by wave and by tripod algorithms may coincide. But in the general case of irregular standpoint sequence, algorithms synthesize different gaits.

The designed algorithms of this level generated support schedule for both constant and variable velocity of the body in the general case for curved route. The body rotation and the vertical component of body velocity might be taken into consideration.

On the third level two versions of standpoint planning algorithms were designed which were able to generate standpoint sequence for an arbitrary curved route on the support surface with small-scale roughness. It was assumed that each point of the surface might be used as a standpoint.

Some algorithms were designed for generating special irregular standpoint sequence for overcoming obstacles.

The fourth-level algorithms formed body motions for a curved route under the above mentioned condition relative to the support surface. Some cases of overcoming obstacles were considered.

Figure 5 presents an example of the walker´s locomotion along the curved route. At first the vehicle moved along the rectilinear segment AB. Then, at point B, it changed its route and began walking along the circle of the prescribed radius around the object located inside the circle (part BCB). At point B the walker continued its previous route (segment BD).

The problem of overcoming isolated obstacles of some types was investigated. An obstacle may be considered as an isolated one when it is located on the support surface which all points might be used as standpoints. For some obstacles it appears un-

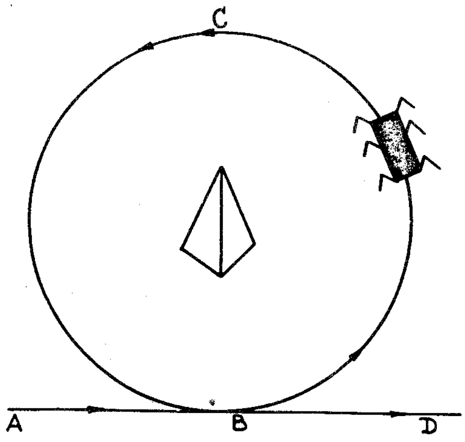

Fig. 5. Locomotion along the curved route.

desirable or impossible to use points of the support surface in the vicinity of the obstacle due to geometrical restrictions associated with the neighbourhood of the obstacle.

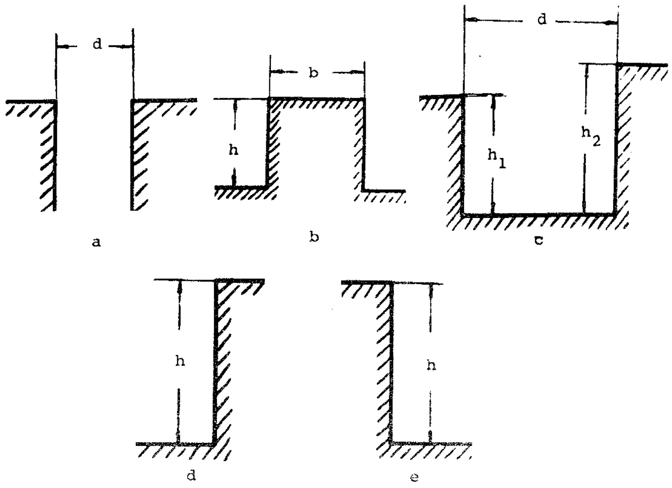

Fig. 6. Some types of isolated obstacles
(a) cleft; (b) boulder; (c) pit;
(d) step up; (e) step down.

Some types of isolated obstacles are shown in Figure 6. One parameter obstacle "cleft" (Fig. 6a) is functionally equivalent to the domain forbidden for standing the legs. There are no geometrical restriction in the vicinity of the "cleft".

Two-parameter obstacle "boulder" (Fig. 6b), on the contrary, creates two restricted spots close to it. The spot before the boulder is undesirable because of possibility to touch the boulder in the support phase. The body of the boulder can make it impossible to stand leg-tip in the spot after the obstacle. It is permissible to stand legs of the walker on the boulder; it is even desirable.

The bottom of the three-parameter obstacle "pit" (Fig. 6c) may be used to stand legs on it except two spots near the walls.

It should be noted that "cleft", "boulder", and "pit" from the geometrical point of view may be regarded as a combination of more simple obstacles of the types "step-up" and "step-down" (Fig. 6d, e). If the longitudinal dimensions of the upper part of the boulder or those of the pit bottom are large enough, the boulder and the pit may be interpreted as two separate isolated obstacle of the "step" type. If the "steps" are positioned one after another rather close, there exists interference between them, and it is apparently, more reasonable to treat such a combination as a special type of obstacle with its own special method for solution.

Some algorithms were designed for decision-making concerning the reasonable actions of the walker overcoming the obstacle. It was assumed that all necessary information about the type and geometrical parameters of the obstacle are available and may be used by a decision-making algorithm.

As to the methods of overcoming obstacles, it was assumed that the higher level might be involved only in case of real need. For instance, if adaptation to small scale obstacles can be made by means of level "leg", this must be done. If this appears impossible, the special standpoint sequence and appropriate support schedule must be generated. If necessary, the special body motion has to be used.

The algorithms for overcoming the cleft-type obstacle were designed in greater detail. A special classification block estimated the situation: standpoint sequence parameters, cleft width and its position relative to the walker. Depending on the situation analysis results the following decisions about the regime could be made:

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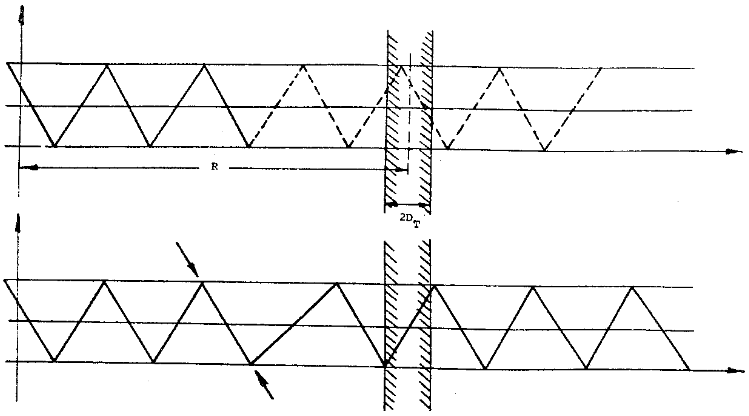

Fig. 7. Modification of standpoints sequence by shifting two standpoints.

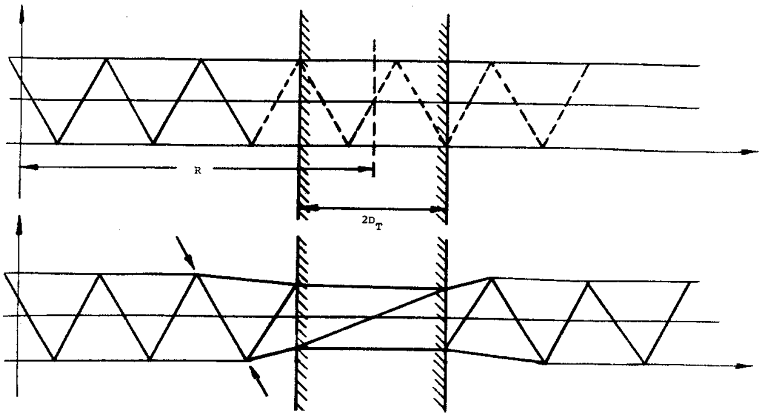

Fig. 8. Modification of standpoint sequence by diminishing its width.

2. It is necessary to make longer one stride before the cleft by changing the position of two standpoints and shifting them in such a way that one of them, the nearest to the cleft, would be positioned on the brink. The further development of standpoint sequence may be regular, as before the cleft.

3. It is necessary to position four standpoints on the brinks of the cleft (two on each brink) and to rearrange some other standpoints.

4. To apply regime 3 but shift standpoints on the brink closer to the axis of the standpoint sequence.

5. The body of the walker must be lowered, and regime 4 must be applied.

The standpoint sequences in Figure 7 correspond to regime 2, while those in Figure 8 correspond to regimes 4 and 5.

The regimes 1 - 5 are listed in order of growth of their complexity and their feasibilities. According to the basic principle, the classification block tried to determine subsequently the possibility of using regimes 1 - 5, beginning from regime 1, and adopted the first of them which provided successful negatiation of the cleft. A block-diagram of the classification block is shown in Figure 9.

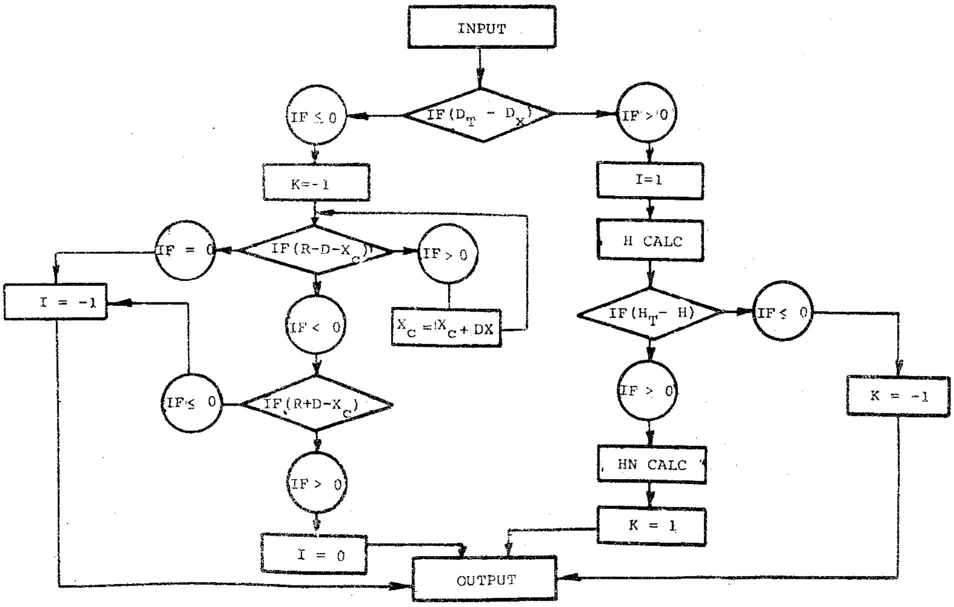

Fig. 9. Block-diagram of the situation analysis algorithm

Such an approach is evidently applicable to designing reasonable methods of overcoming other types of obstacles. It should

be noted that for a pit rather deep, or for a boulder rather high, or for an obstacle like the one in Figure 11 it may be necessary to tilt the body of the walker and change its pitch angle in an appropriate way as a function of time (Figs. 10, 11). It is evident that when analysing the obstacle, this regime, as the most complicated one, has to be tested in the last turn.

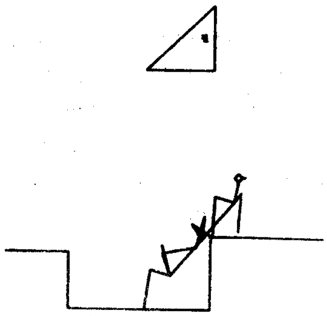

Fig. 10. Overcoming pit with body tilting.

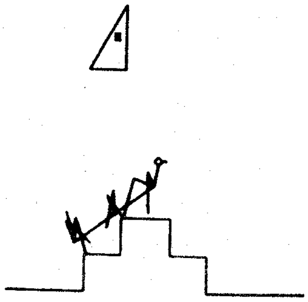

Fig. 11. Climbing over a complicated obstacle.

The investigation carried out confirmed that observation on the display screen of the moving image of the vehicle walking on the terrain is a very effective method for testing the control algorithms and estimating their properties. The motion picture made from the CRT of the display unit gives an idea of the effectiveness of the walker control algorithms.

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