PROBLEMS OF SELECTING A GAIT FOR AN INTEGRATED LOCOMOTION ROBOT

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Abstract. In controlling the locomotion of the walker there appear problems associated with the necessity of constructing coordinated motion of the body and legs which ensures accomodation to irregularities of the terrain being overcome. The paper considers algorithms for selecting supporting points for legs and for gait synthesis at a prescribed curvilinear motion of the walker over the terrain with complex relief.

Introduction* In case of a uniform rectilinear motion of the walker over a plane it is most natural to select the gait, footholds and leg motion schedule on the base of some principles of regularity, using, for example, periodic walking "step-to-step", with constant velocity /I-3/.

While walking over the terrain with complex relief it is sometimes impossible to realize such a uniform motion. Indeed, footholds may be arranged on the terrain irregularly, as there exist areas forbidden for placing the legs (clefts, steep slopes). If the distance between footholds is long and the transfer time is so short, that the transfer velocity turns to be higher than the allowable one, the walker should decrease the velocity of its motion over that segment of the trace. Thus even if the surface irregularities are quite negligible for the walker's body to move keeping a horizontal position without touching them, a uniform motion may appear to be unrealizable.

If surface irregularities are rather appreciable then it is necessary to designing the body motion lest it should touch them. In this case linearity of the body motion is disturbed and uniform motion becomes unrealizable too.

If information about the terrain is being obtained during the motion then such cases may take place when it is impossible to predict motion for lack of information owing to the terrain irregularities intercepting field of view. This problem may be solved by organizing interaction, a kind of dialogue, between the information system and motion design system (MDS). The interaction leads to adrupt decelerations and to disturbances of regularity and uniformity of motion.

Thus, principles of regularity, periodicity and uniformity of legs-and-body motion usea for constructing the gait, the leg motion schedule and for selecting footholds may be appreciably at variance with the requirement that the walker should be accommodating to the terrain relief. To solve the problem of the best accommodation of the walker to the relief accidents it was found necessary to develop algorithms for selecting the gait, footholds and leg motion schedule without any restrictions, associated with a prescribed pattern of motion.

Algorithms for selecting the gait, footholds and leg motion schedule depend appreciably on the availability or lack of adequate information about the terrain at the moment when the motion is being formed. If the information about the terrain is adequate it is possible to predict footholds forward along the trace to the extent which doesn't permit to get into "blind alleys", i.e. into positions when the walker cannot proceed with its motion in the scope of the prescribed gait. The algorithm of "wave gait** synthesis /I, 5/ *otters* a simple way of designing the walker's motion which does not lead to "blind alley" situations. However, the algorithm requires predicting for so a long distance forward along the trace that in case of unavailability of adequate information about the terrain this algorithm may be found to be unrealizable.

In references /3-5/ there was considered a method for solving the problem of choosing the footholds, the leg motion schedule and the body position for a prescribed "gallop" gait in case of unavailability of adequate information! there the case of locomotion over cylindrical surface was investigated.

The investigation of locomotion over cylindrical surface has shown that in order to overcome complex terrain in the absence of adequate information about the terrain it is necessary that the algorithms for choosing the gait, footholds and leg motion schedule should provides

1. Possibility of dialogue with the information system aiming at improving the walker's passabilityt

2. Locomotion over arbitrary trace being chosen by the system of trace selection in the process of locomotion with the object of by-passing large obstacles;

J. Possibility of varying the velocity of the walker's motion without additional recalculations of locomotion parameters:

4. Possibility of realising any type of gait allowable from the viewpoint of static stability to ensure getting out of "blind alley" situations.

The solution of these problems was found by describing the walker's motion in a certain "space of states" offered in the papers by R.Tomovic and R.McGee and with the use of estimates of situation in that space at each instant of motion which were suggested by A.S.Narin'jani and V.P. Pjatkin in their conversation with the authors. As the investigation showed, a more rational method of gait controlling proved to be the method of predicting a situation in the space of states and of choosing adequate actions needed at some key instants of locomotion which are defined by predicting.

Below the paper describes the structure of motion design system, introduces definitions of a motion trace, of the walker's state and of the walker's gait. Next, algorithms of motion designing are described inducting algorithms of predicting, calculating the sequence of walker's states, and choosing footholds.

System structure. The system for simulating the walker's motion consists of two units: a computing unit and an executive one. The computing unit simulates algorithms to be loaded into the walker's on-board digital computers, and the executive unit simulates the real walker.

The computing unit generates control signals used by the executive unit for simulating the walker's locomotion with demostration on a DC display and for shaping information signals characterizing quality of execution.

Motion trace. Motion designing is implemented with the use of two coordinate systems - absolute one (O, ξ, η, ζ) and relative one (P, x, y, z) (fig. I). The relative coordinate system is rigidly coupled with the walker's body. All parameters of the walker are given in the relative coordinate system.

The trace of motion is the curve $\{\xi(s), \eta(s), \beta(s)\}$ in three-dimensional space (ξ, η, β) where ξ, η - coordinates of projection P on the plane $O\xi\eta$, β - the angle between the projection of PX - axis on the plane $O\xi\eta$ and $O\xi$ - axis (the walker's body yaw angle). The trace parameter S was taken to be equal to the length of the curve between the reference point $\{\xi(0), \eta(0), \beta(0)\}$ and the current point.

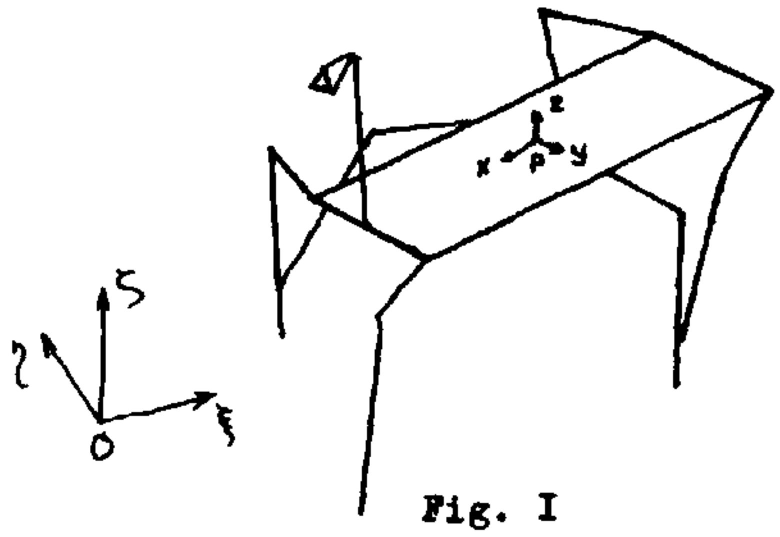

Fig. I

Gait. At each instant of time the walker's state from the point of view of its gait is characterized by the set of legs supporting or being transferred, i.e. by the sixdimensional vector $q = \{q^1, q^2, \ldots, q^6\}$ which consists of zeros and units. In addition q^i = I if leg is supporting, otherwise q^i = 0 /6/. At the moment of ligting or placing any legs on the terrain the walker's state q is changed. The walker's gait may be defined as a sequence of states q_n, n = I, 2,... /2/. Fig. 2 shows the periodic sequence of states corresponding to the tripod gait /I/. If the sequence q_n is periodic then one may say that the gait is cyclic, and the sequence of states being realized within a period is called a cycle. The investigation of a certain class of such gaits was carried out in references /I-4/.

q_1 = (I I I I I I)
q_2 = (I 0 I 0 I 0)
q_3 = (I I I I I I)
q_4 = (0 I 0 I 0 I)
q_5 = (I I I I I I)
q_6 = (I 0 I 0 I 0)
. . . .

Tripod gait

Fig. 2

Given the sequence of states $q_n = \{q_n^1, q_n^2, \ldots, q_n^5, q_n^6\}$, it is convenient to introduce six binary fractional numbers $\alpha_1, \alpha_2, \ldots, \alpha_6$ lying in the range from zero to unit so that the digit n in the mantissa of number α_i is equal to q_n^i. Vector $\alpha = \{\alpha_1, \ldots, \alpha_6\}$ describes entirely the gait of a six-legged walker (fig. 3).

α_1 = 0.III0III0III0... = I4/I5
α_2 = 0.I0III0III0II... = II/I5
α_3 = 0.III0III0III0... = I4/I5
α_4 = 0.I0III0III0II... = II/I5
α_5 = 0.III0III0III0... = I4/I5
α_6 = 0.I0III0III0II... = II/I5

Tripod gait

Fig. 3

Gait α may be realized as a statically stable one only in case when in any state approptiate to it, at least three legs are in the supporting phase. A necessary (but insufficient) condition for it is the following inequality

$$\sum_{i=1}^{6} \alpha_i \geqslant 3$$

If all the gaits of the six-legged walker are identified with a unit six-dimensional cube then unstable gaits will be dense throughout it. Therefore there exists no continuous functional $f(\alpha)$ which would separate stable gaits from unstable ones.

Motion pattern constructing. The walker's motion constructing was subdivided into three stages:

- Global prediction on S. This stage of designing incorporates computing the state sequence for the walker to implement, along with its footholds, leg motion schedule and body motion. The depth of prediction amounts to an order of two walker's body lengths. Computation is performed in the absolute coordinate system.
- Local prediction on S. This stage incorporates computing leg transfer trajectories. It also incorporates computing foot positions for all the legs in the relative coordinate system with such

a step ΔS that in order to calculate intermediate foot positions with a required precision it is sufficient to carry out linear interpolation. The depth of prediction amounts to an order of one fourth of the walker's body length.

- The generation of control signals for the executive unit. This part of the algorithm is applied in real time. A correspondence is set up between parameter S and the time so that the motion velocities of all the legs could not exceed the allowable ones. This stage also incorporates processing the signals received from the executive unit.

Global prediction. At this stage the walker's motion is described as a sequence of states which are computed by using a special algorithm. For each state calculation of footholds is made, along with their existence segments. The existence segment of a foothold is a segment of the trace on which the possibility exists for a leg being in motion along it to be in the supporting phase and, in addition, the leg reaches this foothold without touching the other legs and the surface. The calculation of the existence segment of each state is made, i.e. of the trace segment on which the footholds corresponding to a given state exist all together and provide locomotion static stability. The necessary and sufficient condition for implementing a stable motion is the existence of a non-empty intersection of the existence segment of any two successive states. If the motion throughout the selected sequence of states cannot be realized then a new sequence of states is calculated.

Calculation of states- The calculation of a state sequence is performed either according to a rigid scheme (for example, tripod and gallop gaits are set by vector α, as defined above) or on the basis of some rule. Simulation of the rule indicated below was carried out.

Let Q_0 be the current state, $[S_1^0, S_2^0]$ its existence segment, $[S_1^i, S_2^i]$ – the existence segment of the foothold leg i. If the leg is in the transfer phase, then it is believed that $S_1^i = -\infty$, $S_2^i = +\infty$.

Let's find i_0 under the condition

$$S_2^{i_0} = \min_{i=1,2,\dots,6} S_2^i$$

i.e. leg i_0 may be in the supporting phase less than all the other legs.

Hence, sequence $Q_0 \to U_{i_0}$ is formed, where U_{i_0} – the state differing from the prededing one by the leg i_0 being in the transfer phase. If this sequence cannot be realized then another sequence $Q_0 \to U_j \to D_j \to U_{i_0}$ is formed, where the state D_j differs from the preceding one by the leg j being in the supporting phase, i.e. an attempt is made to transfer j - leg to a new foothold so that it would be possible to transfer i_0 - leg. if none of these sequences is realizable then sequences with twin and triple leg transferring are formed.

$$Q_0 \to U_{jk} \to D_{jk} \to U_{i_0}$$
$$Q_0 \to U_{jkl} \to D_{jkl} \to U_{i_0}$$

Calculation of footholds. Let changing over from state Q_0 to state Q_1 results in transferring legs $i_1, \dots, i_k$ $(k = 1, 2, 3)$ to the supporting phase. The calculation of footholds for these legs is secured by performing the iteration process on S - parameter of truncating the surface domains which are allowable for placing legs.

The initial iteration value S_1 is taken from:

$$S_1 = S_2^0\,,\quad S_1 = \frac{1}{2}(S_1^0 + S_2^0)\,,\quad S_1 = \frac{1}{3}(2S_1^0 + S_2^0)$$

depending on whether among the legs being placed there are back, intermediate and fore legs, respectively.

Each iteration step consists of the body position calculation, and the domains allowable for placing legs are truncated according to the following conditions;

I) Reaching the truncated segment

of the domain:

2) Non-touching the neighbouring lege:

3) Non-touching the surface.

The domains remained after truncation must incorporate points which ensure the walker's static stability at the initial moment of the state existence s_1 If such points exist, a step forward is made. Otherwise a bisection of the iteration step is made with retrogression on s .

At the end of the iteration process, the domains allowable for placing legs are narrowed up to the size of an execution error, therefore they may be taken to be footholds. The right end of the chosen footholds existence segment signifies the value of parameter s' , to which the iteration process has been reduced. The left end is s_1

Conclusions. The algorithms described above were simulated on the display system at the Institute of Applied Mathematics, the USSR Acad.Sci. Tests were carried out by displacing the vehicle along curvilinear trace with a varying radius of curvature, over surface with small domains allowable for placing legs (of the order of 4 per cent of the total area). Simulation has shown that the system described can function in real time and enables to construct the walker's motion for rather complex regimes (turn on place, motion sideways and so on).

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