Force control in locomotion of legged vehicle and body movement for mounting operations

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Abstract : *New results on the development of adaptive six-legged walking robots and their control systems are presented. The major parts of the paper considers control of foot forces distribution and control of body motion based on the information about the main force vector acting on the vehicle. We developed and experimentally tested algorithms for the inserting and drilling operation based on the force control. Rectangular and hexagonal vehicles are considered.*

Keywords : Walking robot, force sensing and control, active compliance and accommodation.

1. Six-legged robots

A rectangular vehicle ("Masha") was developed at the Institute for Mechanics of the Moscow State University and the Institute for Problems of Information Transmission of the Russian Academy of Sciences (fig.1) [1]. A hexagonal vehicle ("Mag") was developed at the Fraunhofer Institute for Factory Operation and Automation (fig.2) [2].

Both vehicles have six legs with three powered degrees of freedom each. Three-component force sensor are mounted in the shanks. The legs are powered by electrical drives with gear reducer and are equipped with joint angle potentiometer sensors (position servosystem). Three-component force sensors are mounted into the leg shanks together with the amplifiers. Each foot has three passive degrees of freedom and a tactile sensor to measure contact with supporting surfaces. The control systems of the robots consists of lower and upper levels [1-3]. The body of the rectangular vehicle carries a gyroscopic attitude sensor to measure the pitch and roll angles of the body.

The upper level of the control systems are supervisory. It prescribes such motion parameters as gait pattern, track width, clearance, and the locomotion cycle parameters. The main coordinate systems of the vehicles are:

$OX_{0,1}X_{0,2}X_{0,3}$ earth-fixed axes describing the surface over that the vehicle moves, $OX_1X_2X_3$ - axes rigidly related to the body with origin of the body centre, $O^{(i)}X_1^{(i)}X_2^{(i)}X_3^{(i)}$ $(i = 1, 2, ..., 6)$- axes connected with i-th attachment points of the legs to the body (fig.3).

Radius-vector $\overline{R}$ denotes the position of the vehicle centre, $\bar{r}^{(i)}$ describes the position of the end of i-th leg with respect to the vehicle centre and $\overline{X}^{(i)}$defines the position of the leg end with respect to the attachment point.

The position of the leg end is defined as $\overline{R}^{(i)} = \overline{R} + \bar{r}^{(i)}$ Differentiation of this relation yields

$$\frac{d\overline{R}}{dt}^{(i)} = \overline{V} + \frac{d\bar{r}}{dt}^{(i)} \tag{1}$$

where $d\overline{R}^{(i)}/dt$ is the absolute velocity of the leg end, $\overline{V}$ is vehicle velocity, $d\bar{r}^{(i)}/dt$ is the relative velocity of the end of i-th leg. Body motion is, obviously, defined by that of the supporting legs only, for which $(d\overline{R}^{(i)}/dt) = 0$, hence $(d\bar{r}/dt) = -\overline{V}$. This equation may be rewritten in terms of projections on body axes $OX_1X_2X_3$ in the following form

$$\frac{d\bar{r}}{dt}^{(i)} + \overline{\omega} \times \bar{r}^{(i)} = -\overline{V} \tag{2}$$

where $\overline{\omega}$ is the absolute angular velocity of the robot body. Under given $\overline{\omega}$ and $\overline{V}$ this relation uniquely defines the trajectories of legs in the support phase. If leg tips are motionless, their relative motion is exactly defined by the body motion. Thus, a coordinated control of the legs in the support phase ensure the prescribed motion of the body in terms of its linear velocity $\overline{V}$ and angular velocity $\overline{\omega}$.

Initial conditions for this system of differential equations are taken from outputs of an other unit. The output of the manoeuvring unit is leg end trajectories defined in the form of Cartesian coordinates in $O^{(i)}X_1^{(i)}X_2^{(i)}X_3^{(i)}$.

The position control system enables the computation of commanded motion of the leg tips and positional feedback to track this commanded motion. Force feedback is added to the positional control system. Beside the computation of commanded forces and leg position corrections, force feedback implements a distribution of vertical and transversal forces, leg sinkage during soft soil locomotion.

2. Force control

By using force information, it becomes possible to solve a large number of tasks. The force control is needed to raise the adaptability of the vehicle to irregular terrain, to distribute the foot forces in locomotion over rigid and soft soil. Control of these foot forces makes it possible to reduce loads on the structure and energy consumption of the leg drives. In locomotion over complex terrain, the horizontal force components may be controlled so that contact forces are within the friction cones.

Another set of tasks - moving through a labyrinth or into a pipe without vision guidance, crawl under an obstacle, mounting of parts by means of the body vehicle - can also be solved by means of force feedback.

2.1. Active compliance

In order to understand the behaviour of a system with foot force feedback, suppose the servo systems tracks the commanded coordinates of the leg end to a high degree of accuracy.

Write the radius vector $\bar{r}^{(i)}$ of the i-th leg in the body-fixed coordinate system as the sum of several terms $\bar{r}^{(i)} = \bar{r}_p^{(i)} + \Delta\bar{r}^{(i)} + \delta\bar{r}^{(i)}$, where $\bar{r}_p^{(i)}$ is the commanded position calculated by the leg motion control algorithms, $\Delta\bar{r}^{(i)}$ is the elastic displacement of the leg-end, and $\delta\bar{r}^{(i)}$ is the commanded position correction.

Support reaction in the i-th leg $\overline{F}^{(i)}$ and elastic displacement of its end are related as follows:

$\overline{F}^{(i)} = C\Delta\bar{r}^{(i)}$. Here C is the positively defined symmetric matrix of mechanical leg stiffness.

Because of the force feedback, the positional servosystem receives the leg position, which differs from the program position $\bar{r}_p^{(i)}$ by

$$\delta\bar{r}^{(i)} = \Lambda^{(i)}(\overline{F}^{(i)} - \overline{F}_p^{(i)}) \qquad (3)$$

where $\Lambda^{(i)}$ is the symmetric positive definite feedback gain matrix, $\overline{F}_p^{(i)}$ is the command force vector. If the measured force $\overline{F}^{(i)}$ differs from the commanded force $\overline{F}_p^{(i)}$, the leg end displacement is proportional to the difference. Such a behaviour of the system is similar to that of an elastic spring with a mechanical compliance Λ and is called active compliance. Active compliance can be controlled by varying the elements of the matrix $\Lambda^{(i)}$ and the commanded forces $\overline{F}_p^{(i)}$.

In this case the control law of drives can be written as $\overline{U}^{(i)} = G_x(\overline{X}^{(i)} - \overline{X}_p^{(i)}) - G_f(\overline{F}^{(i)} - \overline{F}_p^{(i)})$, where $\overline{U}^{(i)}$ - components of voltage vector, $\overline{X}^{(i)}$, $\overline{X}_p^{(i)}$ - measured and program values of position, respectively, G_x, G_f - diagonal coefficient matrix of position and force feedback, respectively.

A multi-leg walking robot is a mechanical system statically indeterminate with respect to forces acting on its legs (foot forces).

In the presence of active compliance the distribution is determined by the matrix $\Lambda^{(i)}$ and the commanded forces $\overline{F}_p^{(i)}$. If the compliance is sufficiently high, small positioning errors have no noticeable effect on the force distribution. In this case the forces $\overline{F}^{(i)}$ are equal to the commanded forces $\overline{F}_p^{(i)}$ if the latter satisfy the static equilibrium equations.

In locomotion over soft soil, it is necessary to correct the position of each leg with respect to their sinkage into soil. The computation of the leg sinkage is closely related to the computation of forces. The interaction of the above control processes is described by the equation

$$\bar{r}^{(i)} = r_p^{(i)} + \Lambda^{(i)}(\overline{F}^{(i)} - \overline{F}_p^{(i)}) + s_p^{(i)} \qquad (4)$$

For the locomotion of our robots there were developed and experimentally tested algorithms for load and sinkage control for walking over rigid and elastically deformable surfaces, over a surface with irreversible deformation and locomotion between planes forming a dihedral angle. Algorithms are based on the control principle of active compliance [4-6].

2.2. Step adapt on

For moving a vehicle over a structured terrain we need a adaption to a different ground clearence for each leg. The step cycle must be modified in order to get a correct ground contact. To get the ground contact information the foot force information is used.

While touching the ground the foot force is rising in dependence on the ground properties: for rigid ground the force is rising quickly, for soft ground slowly. The ground touching phase is ending, if the desired foot force distribution is reached. Together with active compliance we get an adaptable step. By analyzing the foot force depending on the foot position the soil softness can be measured. This is needed to adapt the step cycle in the transfer phase for enough foot clearence.

A similar algorithm is used for obstacle detection and crossing. During the transfer phase the touch detection algorithm is activated in transfer direction. An obstacle is detected if the foot force reaches a prescribed value. At this moment the foot should be stopped.

Combining the obstacle detection with the active compliance the foot begins stopping while the acting force is rising and before the force level for obstacle detection is reached. In this case a hard hit onto the obstacle is avoided.

An adapted step cycle is shown in figure 4. The step was adapted with ground detection and active compliance. During the transfer phase an obstacle was detected. A corrected transfer phase path was calculated to avoid the obstacle.

2.3. Force distribution in statically undetermined mechanical systems

Force control should improve the vehicle performance at soft soils. When moving along a nonrigid surface, leg subsidence into the soil must also be controlled by correction of their commanded position.

Several control algorithms of vehicle motion using a priori knowledge of subsidence vs. load dependence for each leg are possible. For example, leg motion can be corrected by subsidence computed from the commanded load on the leg. In this case the commanded load is to be tracked by means of force feedback. With another algorithm each leg sinkage is computed from the desired force in this leg if no force feedback is activated. Both described algorithms were experimentally tested during the locomotion over a thick layer of porolon. Subsidence vs. load dependence for the sample used can be treated as simple, linear and equal in different points.

Ground clearance fluctuations of the vehicle were not more than 1 cm, attitude fluctuations not more than 1 deg with maximal leg subsidence being 5 cm.

However, the characteristics of the real soils are far from the linear elastic model.

We have investigated the mechanical load-sinkage properties of soil. Such curves for a number of soils and synthetic materials were obtained experimentally with the aid of the vehicle leg. All legs but one stayed on the rigid support; the remaining leg was placed on the soil or a synthetic material to be investigated. The load on this leg was repeatedly changed from zero to a maximum value (about 100 N) and vice versa. The leg sinkage was determined by means of joint angle sensors, and the load was measured by means of a force sensor. Some of the experimental load-sinkage curves are shown in fig. 5. A maximum load on the leg was 120 N, with the foot area 30 cm^2, resulting in a pressure of 40 kPa.

As seen from fig. 5 and known from literature [7] in natural soil the sinkage is irreversible. Most natural soils have completely irreversible deformation characteristics. Such soil behaves as an absolutely rigid support if the load on the foot becomes less than a maximum value already achieved. Note that the properties of natural consolidating soil may differ considerably, even within small spatial variations.

3. Force control by active accommodation

Control of moving body can be solved by means of control based on the information about the main force and torque vectors acting on the vehicle body. If the commanded vectors of linear and angular body velocities lineary depend on the force and torque, then the vehicle body will move in accordance with the "accommodation" or "generalised damping" concept [8]. The control law for the position of leg ends is $\overline{U}^{(i)} = T^{(i)} G_x(\overline{V} - \overline{V}_p)$ where $\overline{V}$, $\overline{V}_p$ are measured and commanded values of body velocities, $T^{(i)}$ is the transformation matrix from axes $OX_1X_2X_3$ to axes $O^{(i)}X_1^{(i)}X_2^{(i)}X_3^{(i)}$. $\overline{V}_p$ is calculated as

$$\overline{V}_p = G_f(\overline{F} - \overline{F}_p) \qquad (5)$$

where G_f - matrix of accommodation. Force vector $\overline{F}$ can be determined as the sum of the appropriate force components acting on the legs or, alternatively, by means of a force sensor mounted into the operating tool or object, connected with the body.

In this way can be solved, for example, the problem of bringing a tool mounted on the body of the vehicle into contact with an object (part), whose position is unknown, and to maintain this contact with a specified clamping force, or the problem of moving a tool along the surface of object whose shape is not known in advance.

3.3. Inserting operation

The above mentioned approach is demonstrated for the insertion of a tube with the diameter d_0 into a hole of an external object. The tube is rigidly connected to the body of the hexapod vehicle (fig. 6) by a force sensor. Its axial direction is parallel to OX_1 which is fixed to the body and with its origin in the body centre. The surface of the external object is a funnel-shaped hole with a diameter of $d > d_0$ (see fig. 6,7).

In general, the task of inserting the tube into the hole can be solved by motion of walking robots' body using all six degrees of freedom. In our example, we made a simplification and solved this task only by planning the linear motion of the robots' body.

For the solution of this problem we used a method based on the compensation of linear errors of the body position. The basic principle of this method is the measurement of reaction force components due to contact of the tube to the funnel-shaped surface and moving the body of robot in such a way that the reaction forces will be minimalized. Two algorithms were analysed. The first algorithm is based on the compensation of independent displacements of robots body. The velocity components of the body, $\overline{V}_p = col(v_{px}, v_{py}, v_{pz})$, are calculated as (5).

We consider two basic phases of the insertion procedure: motion along a mechanical link and maintainance of a given contact force.

During operation the tube moves towards the hole and touches the inner side of the funnel. During this motion the force components are determined.

Due to the force feedback, the body of the vehicle is displaced in the direction of the reduction of lateral force components and force contact is maintained equal to the programmed value. The accommodation matrix G_f is set diagonally. Its elements are adjusted so that they are big for movements perpendicular the hole and small for movements along the tube axis.

Our experiments have shown that there can occur a loss of contact between the tube and the surface of funnel-shaped hole. In the force reaction measurements this phenomena is observed as a momentum change of the force components, particulary a change of the longitudinal force component. The main reasons for this are bad coordination of velocity components and inaccuracy in computer servosystems.

The second elaborated algorithm of body motion control is based on the complex motion as the superposition of two "basic" motions - motion in the normal direction to the surface of the object and motion along the tangent to the surface [9]:

$$\overline{V}_p = \overline{V}_n + \overline{V}_\tau = \lambda(F - F_p)\overline{n} + V_\tau \overline{\tau} \qquad (6)$$

Here, $\overline{n}$ and $\overline{\tau}$ are the vectors of the outer (outside) normal and the tangent with respect to the surface, $V_\tau = const > 0$ is the programmed value of the tube velocity along the tangent to the surface of object (contour velocity), $F_p = const > 0$ is the programmed value of the normal component of the contact force to be maintained, $\overline{F}_n$ is normal force component, $\lambda > 0$ is a constant. If the friction between the tube and surface is absent or kown then the vectors $\overline{n}$ and $\overline{\tau}$ can be determined from force sensor. The previously mentioned relationship (5) describes a linear control method, relationship (6) is a nonlinear control method. To use (6) in the control system we have to evaluate the force value $\overline{F}_n$ and to find vectors $\overline{n}$ and $\overline{\tau}$ which describe the directions of the body and the tube.

The experimental results have shown that the second control method yields a more uniform tube movement along the funnel-shaped hole and the measured values of force components are very close to the programmed value F_{px}.

The experimental results are plotted in fig. 8. Here F_x, F_y, F_z are forces obtained during the motion of the tube along the funnel-shaped hole, x, y, z are the displacements of the body and tube along axes OX, OY, OZ versus time. The values of $\Delta x, \Delta y, \Delta z$ are calculated relatively to the motionless legs standing on the surface. The diameter of the tube is d=60mm, diameter of the hole d_0=65mm, diameter of the funnel D=230mm, height of the funnel h=110mm.

On the plots one can see the characteristic stages (portion of curves): the motion of the tube to contact with funnel-shaped surface, the motion of the tube along this surface to the centre of the hole and at once (immediately) the insertion of the tube into the hole.

From the start of the motion till the moment of contact the body of vehicle is shifted along axis OX with a velocity proportional to the programmed force F_{px}.

After contact between tube and the surface there arises a force, and the program performs control in correspondence with (6). The contact of the tube to the funnel-shaped surface occurs with normal force $\overline{F}_n$, and the tube is shifting along the cone-type surface. The contact between tube and funnel is never lost.

From the start of motion of the tube into the hole the value of longitudinal force component F_x decreases to zero. This is the switching signal to accommodation control in accordance with (6).

Conclusions

- Information about foot force interactions between robot legs and the surface used by the control system improves adaptation to terrain roughness and provides uniform distribution of forces between supporting legs.
- Force control of legs in locomotion and motion of body for the technological operating have been developed and experimentally tested.
- Information about the main force and torque vectors acting on the body vehicle due to contact with an external object are used to perform assembly and drilling operations.

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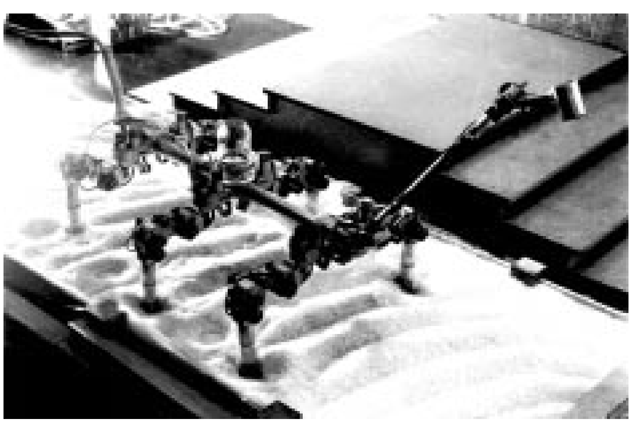

Fig 1: Six-legged robot "Masha"

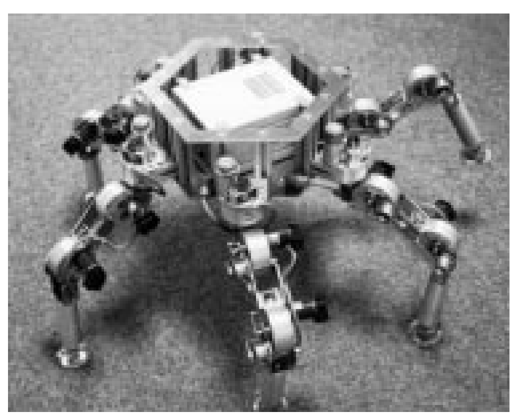

Fig. 2: Six-legged robot "Mag"

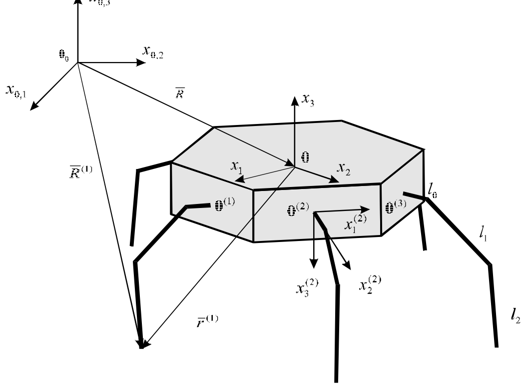

Fig. 3: Coordinate system of the six-legged vehicle

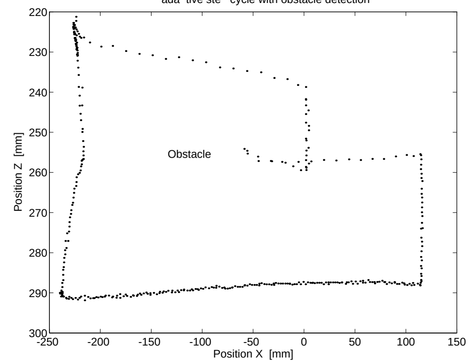

Fig.4: Adaptive step cycle with obstacle detection

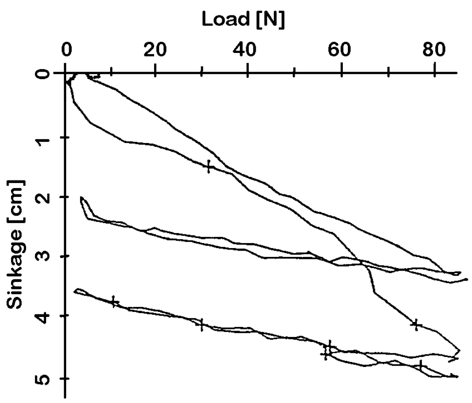

Fig. 5: Load-sinkage curves obtained by the vehicle leg

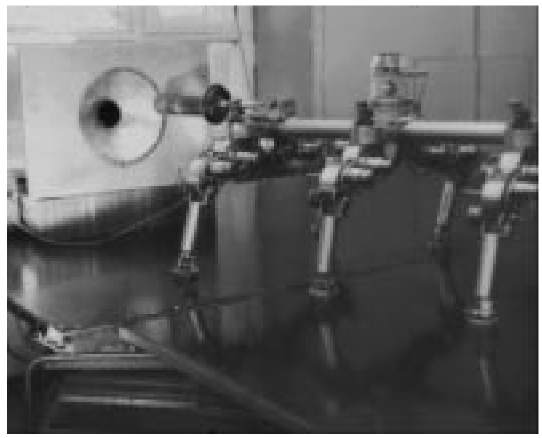

Fig. 6: Photograph of the vehicle during inserting a tube into a funnel-shaped hole

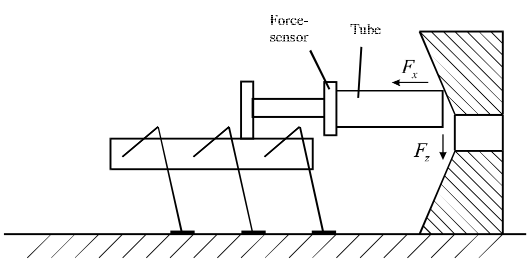

Fig. 7: Inserting a tube into a hole

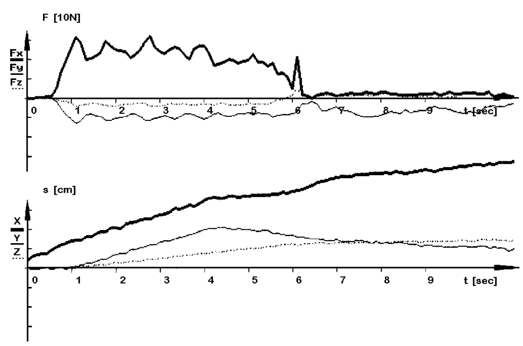

Fig. 8: Experimental results of inserting a tube into a funnel-shaped hole