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Force Control in Locomotion of Legged Vehicle and for Service 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 part of the paper considers force control for step adaptation 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 inserting and drilling operations based on the force control. Rectangular and hexagonal vehicles are considered.

Keywords: Walking robot, force sensing, active compliance, accommodation

1. Introduction

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. 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 (fig.3). Each foot has three passive degrees of freedom and a tactile sensor to measure contact with supporting surfaces. The control system of the robots consists of lower and upper levels [1,2]. 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 system is supervisory. It prescribes such motion parameters as gait pattern, track width, clearance, and the locomotion cycle parameters. 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. Algorithms are based on the control principle of active compliance [3-5].

2. Force control for step adaptation

For moving a vehicle over a structured terrain we need an adaptation 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 ends, 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 an information about soil softness can be evaluated. This is needed to adapt the step cycle in the transfer phase for enough foot clearance.

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 predefined 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 fig. 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.

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 linearily depend on the force and torque, then the vehicle body will move in accordance with the "accommodation" or "generalised damping" concept [6].

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

3.1. Inserting operation

The position of the leg end is defined as $\overline{R}^{(i)} = \overline{R} + \overline{r}^{(i)}$, where $\overline{R}$ is radius-vector of the vehicle centre, $\overline{R}^{(i)}$ is leg end with earth-fixed axes correspondingly, $\overline{r}^{(i)}$ is the end of *i*-th leg with respect to the vehicle centre. Differentiation of this relation yields $d\overline{R}^{(i)} / dt = \overline{V} + d\overline{r}^{(i)} / dt$, where $d\overline{R}^{(i)} / dt$ is the absolute velocity of the leg end, $\overline{V}$ is the vehicle velocity, $d\overline{r}^{(i)} / dt$ is the relative velocity of the end of *i*-th leg. Body motion is, obviously, defined by the supporting legs only, for with is $(d\overline{R}^{(i)} / dt) = 0$, hence $d\overline{r}^{(i)} / dt) = -\overline{V}$. This equation may be rewritten in terms of projections on the body axes in the following form

$$d\bar{r}^{(i)} / dt + \overline{\omega} \times \bar{r}^{(i)} = -\overline{V}\ , \qquad (1)$$

where $\overline{\omega}$ is the absolute angular velocity of the robot body. Under given $\overline{\omega}, \overline{V}$ this relation uniquely defines the trajectories of legs in support phase. Thus, a coordinated control over the legs on the support phase ensures the prescribed motion of the body in terms of its linear velocity $\overline{V}$ and angular velocity $\overline{\omega}$.

This approach is demonstrated for 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 a hexapod vehicle (fig. 5) by a force sensor. Its axial direction is parallel with the OX_1 axis rigidly related to the body 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. 1).

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

For the solution of this problem we used a method based on the measurement of reaction force components due to contact of the tube to the funnel-shaped surface and moving the body of the 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.

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

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 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 to 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 the funnel-shaped hole. In the force reactions measurements this phenomena is observed as sudden changes of the force components, particulary the changes of the longitudinal force component. The main reasons for this are bad coordination of velocity components and inaccuracy in the computer servosystems.

The second elaborated algorithm of body motion control is based on the complex motion as a superposition of two "basic" motions - motion in the normal direction to the surface of the object and motion along the tangent to the surface [7]:

$$\overline{V}_p = \overline{V}_n + \overline{V}_\tau = \lambda \cdot \left(F - F_p\right) \cdot \bar{n} + V_\tau \cdot \bar{\tau} \qquad (2)$$

Here $\bar{n}$ and $\bar{\tau}$ 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 the object (contour velocity), $V_\tau = const > 0$ is the programmed value of the normal component of the contact force to be maintained, $\overline{F}_n$ is the normal force component, $\lambda > 0$ is a constant. If the friction between tube and surface is absent or known then the vectors $\bar{n}$ and $\bar{\tau}$ can be determined from force sensor signals. To use (2) in the control system we have to evaluate the value of force $\bar{F}_n$ and to find vectors $\bar{n}$ and $\bar{\tau}$ which describe the directions of the body with the tube.

For finding $\bar{F}_n$, $\bar{\tau}$ and $\bar{n}$ we suppose that the longitudinal axis of tube and hole are parallel and the tube is moving over the funnel surface without friction.

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} (fig. 6).

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 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. Diameter of the tube is d=60mm, diameter of the hole d_0=65mm, diameter of the funnel D=250mm, height of the funnel h=110mm.

The upper plots show 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 inserting 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 surface there arises a force, and the program performs control in correspondence with (2). The contact of the tube to the funnel-shaped surface occurs with normal force F_n, and the tube is shifting along the cone-type surface. The contact between the tube and the funnel-shapped surface is never lost.

3.2. The force control of vehicles body movement for drilling

Moving of body with a tool for mechanical processing has to be performed by force control.

The drill is mounted on the body of the vehicle by means of a force sensor measuring three components of the force vector (fig.7).

3.2.1. Evaluation of tool orientation in relation to the surfaces' normal direction

For the orientation of the drill which is touching the working surface it is necessary to control the body movement in such a way that the longitudinal axis of the drill is collinear to the normal direction of the parts surface. The point of contact must be constant in time.

Our algorithm utilizes the data from the force sensor for evaluation of the normal direction of the working surface.

While the drill touches the working surface the three force components are measured. From this data the normal direction to the working surface can be controlled in such a way that the lateral components of the force vector are going to minimal values. The longitudinal component of the contact force must be parallel to the axis of the drill (fig.8).

This component has to be constant. In this situation the control method for vehicles body to keep the constant point of contact is

$$V_{px} = k_x \cdot \left(F_x - F_{px}\right),\ \omega_{py} = -k_z \cdot F_z,\ \omega_{pz} = k_y \cdot F_y,\ V_{py} = -\omega_{pz} \cdot R,\ V_{pz} = \omega_{py} \cdot R, \quad (3)$$

where V_{px}, V_{py}, V_{pz}, ω_{py}, ω_{pz} are the linear and angular velocities evaluated by the computer, F_x, F_y, F_z are components of force measured by the force sensor, $F_{px} = const > 0$ is the programmed force which have to keep the fixed OX direction, k_x, k_y, k_z is the feedback gain, R is a constant describing the distance between the coordinate frame and drill end.

After the touch the program starts the drilling operation.

3.2.2. Drilling

For drilling operations the pressing force determines the cutting force which has to be controlled. The cutting force has to be constant at all time in the direction of normal force F_n This force has to be close to F_{px}. The programmed body velocity component V_{px} is calculated in (2). For avoiding jam and tool breakage the control system can compensate for the lateral components of interaction forces which arise during the drilling operation.

Conclusion

Force control of legs in locomotion and motion of body for technological operations have been developed and experimentally tested.

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.

Information about the main force and the torque vectors that acts on the body vehicle coming into contact with an external object and maintaining the given contact force, are used for the assembly and drilling operations.

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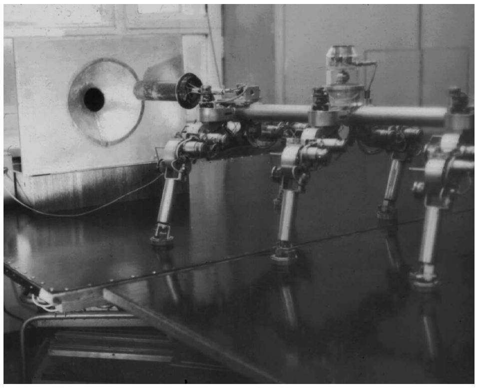

Figure 1. Six-legged robot "Masha"

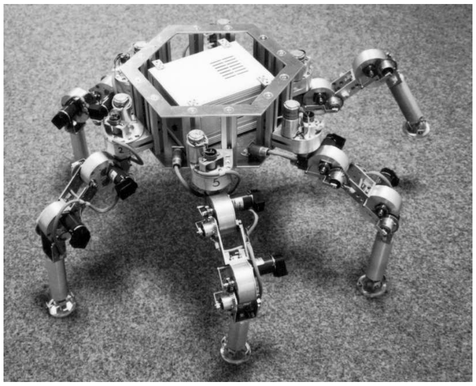

Figure 2. Six-legged robot "Mag"

Figure 3. Force Sensor

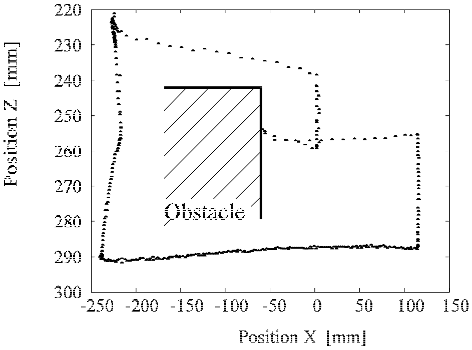

Figure 4. Adaptive step cycle with obstacle detection

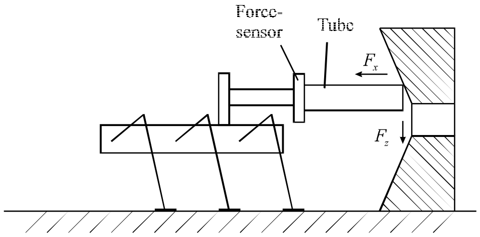

Figure 5. Inserting a tube into a hole

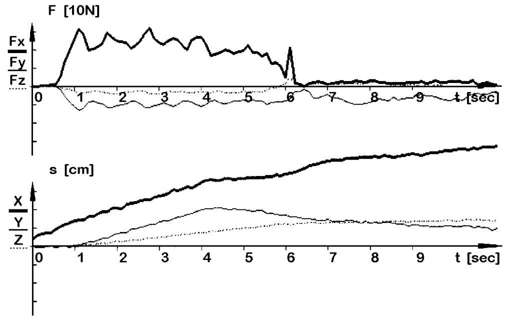

Figure 6. Experimental results of inserting a tube into a funnel-shaped hole

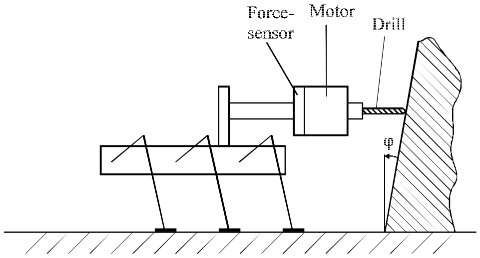

Figure 7. Initial position of vehicle at drilling

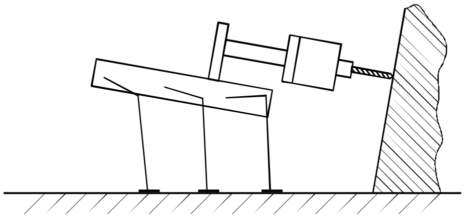

Figure 8. End position of vehicle at drilling