Six-legged robot for service operations

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Abstract

New results on the development of an adaptive six-legged hexagonal walking robot and its control system are presented. The major part of the paper considers control of foot force distribution and control of body motion based on the information about force foot reactions and the information about the main force vector acting on the robot’s body. Inserting and drilling operations based on the force control are considered.

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

1. Introduction

Among mobile robots one may select a special type - walking robots. The use of legs as propulsive devices instead of wheels or tracks enables such robots to move over surfaces with complicated profile, to adapt to practically any surface, overcoming obstacles which for conventional transport vehicles with wheels or tracks are basically insuperable.

Most of researches carried out in field of development of walking robots and their applications are mainly connected with transportation capabilities.

However, only transportation of technological equipment does not bound the capabilities of such robots. They can be used as multi-purpose chassis to perform civil-engineering tasks, mounting, repairing, emergency-and-rescue and others works. Necessary position and orientation of the platform can be achieved by control and motion of the legs standing on the surface. Thus, the controlled platform can be considered as a handling equipment on which can be installed a crane-manipulator, tools, maintenance equipment etc. To perform operations it is necessary to have a force control system. One have to measure the force distribution between the foot legs, the vectors of main force and torque acting on the body vehicle and force reactions by interaction of handling and object, too.

This report presents the results of the work carried out at the Fraunhofer-Institute for Factory Operation and Automation (Magdeburg, Germany), and also at joint research with the Institute for Mechanics of Moscow State University.

2. Six-legged robot and its control system

The kinematical structure is represented schematically in fig. 1 together with the related systems of coordinates. 

$O_0X_{01}X_{02}X_{03}$ is the coordinate system fixed to the surface over which the robot moves: $OX$ - vertical vector unit magnitude; $OX_{12}X_{23}$ - coordinate system fixed to the body centre. Radius-vector $\vec{R}$ denotes the position of the body’s centre, $\vec{r}^{(i)}$ - position of the $i$-th foot with respect to the attachment point.

The vehicle has six identical legs with three controllable degree of freedom each (fig. 2). Furthermore, each foot has three passive degrees of freedom. The legs are powered by electrical drives with gear reducers and are equipped with joint angle potentiometer sensors.

![Figure 1: Coordinate Systems](image-url)
(position servosystem). To measure ground reactions three-component force sensors together with the amplifiers are incorporated into the leg shanks.

The main geometric and mass parameters of the robot are: a hexagonal body with length of side \( a = 180 \text{mm} \), its height \( 120 \text{mm} \); length of the leg links \( l_0 = 75 \text{mm} \), \( l_1 = 130 \text{mm} \), \( l_2 = 200 \text{mm} \). The leg mass is 2.8 kg, mass of the body together with microcontroller and d.c. motor amplifiers is 3.5 kg (total mass of the robot is about 21 kg).

2.1. Control system

The control systems of the robot (fig. 3) consists of upper and lower levels and is based on the idea of the synergy of the quasi-regular gait, which constitutes the main pattern of the motion [1].

The upper level of the control system is supervisory and prescribes such motion parameters as components of linear and angular velocities of the body, gait pattern, track, width, clearance, and some cycle parameters of locomotion. Algorithms of lower level are based on the assumption that the vehicles move slow enough to describe its motion kinematically. The lower level is realised by resources of the main controller and six leg controllers. The local controllers are connected to the main controller which is connected to a PC via a serial link. All controllers are located inside the robots body.

The main controller contains five basic units: master step cycle generator, step cycle modification unit, coordinate transformation unit, sensor signal evaluation, and six leg transformation units.

The master step cycle generator. The tip of each leg moves relatively to the body of the vehicle along a closed trajectory called "step cycle" [1]. The unit contains one generator that creates prototypes of plane step cycles for each leg in some auxiliary Cartesian coordinates. The step cycles are interrelated to preserve given relations between step cycle phases and a sequence of states of the legs.

The step cycle modification unit has several functions. A global modification subunit performs modifications of global geometric (vertical and horizontal) parameters of step cycles.

An individual modification subunit performs changes for each step cycle individually. A step cycle consists of support phase and transfer phase (fig. 4). The transfer phase contains three sections: intrinsic transfer phase, lifting phase of a leg from a surface and lowering phase of a leg to a surface. A transition from transfer phase to support phase takes place either after finishing the lowering phase or from signals of force sensors indicating the moment when the leg steps onto an obstacle.

The coordinate transformation unit provides geometric linkage of prototype trajectories with the body scheme, their scaling, linear and angular shifts of trajectories in the transfer phase.

Sensor Signal Evaluation. This unit operates with force and angle signals and calculates the algorithms of ground detection, force distribution between the legs in locomotion over rigid and soft surfaces [2,3] and obstacle crossing [4,5]. In this unit, a joint handling of internal and external sensordata is performed.

Six leg transformation units have the six cycle generators as input and yield the programmed trajectories for each leg in Cartesian coordinates \( \bar{O}^{(i)}\bar{x}_1^{(i)}\bar{x}_2^{(i)}\bar{x}_3^{(i)} \) - axes, whose origin coincides with the attachment point of the leg.

The leg controllers contain the local leg transformation unit, the sensor transformation unit, and the leg control system.

The local leg transformation unit transforms Cartesian coordinates of programmed vectors \( \bar{x}_p^{(i)} \) into the programmed vectors of joint angles \( \bar{\alpha}_p^{(i)} \).

The sensor transformation unit transforms the force vector \( \bar{F}_x^{(i)} \) measured by force sensor in the shanks to vector \( \bar{F}_x^{(i)} \) in axes \( \bar{x}^{(i)} \) and vector of measured angles \( \bar{\alpha}^{(i)} \) into the vector \( \bar{x}^{(i)} \) in Cartesian coordinates.

The leg control unit consists of the three-dimensional position servocontrol system for each leg. Each leg has its own controller based on a microcontroller INTEL 87C196KR which only controls the according leg. The controller includes the CPU, FLASH-memory and RAM, a PWM output unit (PWM-U), analog input unit (AIU) and a synchronous serial communication unit (SSCU) on the chip. All microcontroller units are connected by a synchronous serial bus (fig. 5).
3. 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.
obstacle, mounting of parts by means of the body vehicle - can also be solved by means of force feedback.

3.1. Force control for step adaptation

For moving a vehicle over structured terrain we need an adaptation to different ground clearance 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 analysing the foot force depending on the foot position an information about soil softness can be measured. 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. In this moment the foot should be stopped.

Combining the obstacle detection with the active compliance the foot begins to stop 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. 6. 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.

3.2. Active compliance

For the description of legs motion we use the coordinate system $OX_1X_2X_3$. Assume voltages of the leg drives as

$$\overline{U}^{(i)} = G_i^{(i)} \left( \overline{V}_p^{(i)} - \overline{V}^{(i)} \right),$$  

(3.1)

where

$$\overline{V}_p^{(i)} = -G_2^{(i)} \left( \overline{r}^{(i)} - \overline{r}_p^{(i)} \right) - G_3^{(i)} \left( \overline{N}^{(i)} - \overline{N}_p^{(i)} \right).$$

Here $i$ is the leg number, $G_1^{(i)}, G_2^{(i)}, G_3^{(i)}$ are the (3x3) feedback gain matrices of velocity, position and force reaction, respectively. $\overline{V}_p^{(i)}, \overline{V}^{(i)}$ are commanded and measured velocity vectors, $\overline{r}^{(i)}, \overline{r}_p^{(i)}$ - radius vectors of realised and commanded position of i-th leg. (vector $\overline{r}_p^{(i)}$ is determined by the joint angles), $\overline{N}^{(i)}, \overline{N}_p^{(i)}$ are measured and commanded values of force reaction in i-th leg.

Expression (3.1) can be transformed into

$$\overline{U}^{(i)} = -G_2^{(i)} \left[ \overline{r}^{(i)} - \left( \overline{r}_p^{(i)} + \delta \overline{r}^{(i)} \right) \right] - G_3^{(i)} \overline{V}^{(i)},$$

(3.2)

where

$$\delta \overline{r}^{(i)} = \Lambda^{(i)} \left( \overline{N}^{(i)} - \overline{N}_p^{(i)} \right).$$

(3.3)

Here $G_1^{(i)} = G_1^{(i)} G_2^{(i)}$. Vector $\delta \overline{r}^{(i)}$ can be considered as position correction to the commanded position of i-th leg tip. $\Lambda^{(i)} = \left( G_2^{(i)} \right)^{-1} G_3^{(i)}$ is matrix of mechanical compliance of the leg. Value $\overline{r}_p^{(i)} = \overline{r}_p^{(i)} + \delta \overline{r}^{(i)}$ means a commanded position, which inputs to the servo-system.

As follows from (3.2), (3.3), when measured force reaction $\overline{N}^{(i)}$ coincides with commanded force reaction $\overline{N}_p^{(i)}$, the leg tip position $\overline{r}_p^{(i)}$ is equal to the commanded value $\overline{r}^{(i)}$. If the force reaction acting on the leg differs from the commanded value, it causes an additional leg displacement proportional to the difference. Such a behaviour of the system similar to that of an elastic spring with a compliance $\Lambda^{(i)}$ is called active compliance \cite{1,6}. Active compliance can be controlled by varying the elements of the matrix $\Lambda^{(i)}$.

The walking vehicle has legs with joint angle potentiometers. Therefore, the commanded trajectories $\overline{r}_p^{(i)}$ in terms of Cartesian coordinates are transformed into commanded joint angles $\overline{r}_c^{(i)}$. Note, that

![Figure 6: Adaptive step cycle](image-url)
\[(\overline{r}^{(i)} - \overline{r}_p^{(i)}) = J_r^{(i)}(\overline{\alpha}^{(i)} - \overline{\alpha}_p^{(i)})\] and expression (3.2) can be written in form

\[\overline{U}^{(i)} = G_i^{(i)}J_r^{(i)}(\overline{\alpha}^{(i)} - \overline{\alpha}_p^{(i)}) - G_i^{(i)}\overline{\alpha}_p^{(i)} ,\]  

(3.4)

where \( J_r^{(i)} \) is the Jacobian from joint angles to Cartesian coordinates of leg tip, \( \overline{\alpha}^{(i)} \) is three-component vector of measured joint angle values. In our case, the velocity feedback is not effective because the drives have a high damping from a high reduction. Consequently in (3.4) \( G_i^{(i)} = 0 \) and the expression (3.4) for voltages can be written as

\[\overline{U}^{(i)} = G_z^{(i)}(\overline{\alpha}^{(i)} - \overline{\alpha}_p^{(i)}) ,\]  

(3.5)

where \( G_z^{(i)} = G_i^{(i)}J_r^{(i)} \) is the feedback gain matrix of the position which is chosen as

\[G_z^{(i)} = \text{diag}\{g_{z1}^{(i)},g_{z2}^{(i)},g_{z3}^{(i)}\} .\]

3.3. Control of reaction force distribution

In order to evaluate algorithms for the control of foot reaction forces we will use a coordinate system \( \overline{OX}_1\overline{X}_2\overline{X}_3 \), rigidly connected with the body of the robot and a world coordinate system \( \overline{OX}_0\overline{X}_1\overline{X}_2\overline{X}_3 \). The desired motion of the body can be described by a radius vector \( \overline{R}_p \), which describes the desired position of the body centre (point \( \overline{O} \)), and a matrix \( A_p^{(i)} \), consisting of the directional cosines between \( \overline{OX}_i\overline{X}_j \) and \( \overline{OX}_0\overline{X}_i\overline{X}_j \). Assuming, that no slippage occurs between ground and feet, the programmed positions \( \overline{r}_p^{(i)} \) of the of the ends of supporting legs have to be given according to:

\[\overline{R}_p + A_p^{(i)} \cdot \overline{r}_p^{(i)} = \overline{R}^{(i)} ,\]  

(3.6)

where \( \overline{R}^{(i)} \) - radius vector of \( i \)-th foot contact point in the system \( \overline{OX}_0\overline{X}_i\overline{X}_j \).

Let the movement of the robot be under control according to formulas (3.2), (3.3), (3.4), i.e. the feet have an artificial compliance. Then the movement of the robot will be somewhat different to the programmed one. It means, the radius vector \( \overline{r}^{(i)} \) of the end points of the feet differs from \( \overline{r}_p^{(i)} \), and (3.6) can be replaced by (3.2)

\[\overline{R} + A^{(i)} \cdot \overline{r}^{(i)} = \overline{R}^{(i)} ,\]  

(3.7)

where \( \overline{R} \) - radius vector of the actual position of central point \( \overline{O} \), \( A^{(i)} \) - actual matrix of directional cosines between \( \overline{OX}_i\overline{X}_j \) and \( \overline{OX}_0\overline{X}_i\overline{X}_j \).

If the deviation between programmed and actual paths is small, so according to (3.6), (3.7) - the following equation holds for the supporting legs with accuracy to second order terms:

\[\Delta \overline{R} + \delta \overline{r}^{(i)} + \Delta \overline{r}_p^{(i)} = 0 \]  

(3.8)

Here, \( \Delta \overline{R} = A^{-1}(\overline{R} - \overline{R}_p) \) is the radius vector, characterising a small linear deviation of point \( \overline{O} \) from the programmed value, \( \delta \overline{r}^{(i)} \) is the vector of small angular deviation of the body orientation, \( \Delta \overline{r}_p^{(i)} \) - radius vector of foot deflection due to elastic deformations, \( \Delta r_0^{(i)} \) - radius vector of the error, affected by the control system, \( \delta r_0^{(i)} \), addition to the programmed value due to force feedback according (3.3).

Vectors \( \Delta \overline{r}_p^{(i)}, \Delta r_0^{(i)}, \delta r_0^{(i)} \) are given in the coordinate system \( \overline{OX}_1\overline{X}_2\overline{X}_3 \). Supporting forces \( \overline{N}_p^{(i)} \) in the \( i \)-th leg and their elastic deformations are connected by \( \Delta \overline{r}_p^{(i)} = \chi \delta r_0^{(i)} \), where \( \chi \) is a positive definite matrix of mechanical stiffness of the leg.

Following we assume, that the foot deflection \( \delta r_0^{(i)} \) due to the artificial compliance is much larger than deflections \( \Delta \overline{r}_p^{(i)}, \Delta r_0^{(i)} \). Ignoring their influence to the force distribution equation (3.8) can be written as

\[\Delta \overline{R} + \Delta \overline{r}^{(i)} = 0 \]  

(3.9)

Assuming the walking robot moves slowly we can neglect the influence of dynamic factors to the force distribution, too. We add to equation (3.3) the static equilibrium conditions:

\[\sum_{i=1}^{6} \overline{N}_i^{(i)} = \overline{N}, \sum_{i=1}^{6} (\overline{r}_p^{(i)} + \delta r_0^{(i)}) \times \overline{N}_p^{(i)} = \overline{M} \]  

(3.10)

with \( \overline{N} \) - gravitational force, \( \overline{M} \) - general torque resulting from the gravitational force in a body fixed coordinate frame.

Conditions (3.3), (3.9), (3.10) yield a closed system of equations to determine \( \Delta \overline{R}, \Delta \overline{r}^{(i)}, \delta \overline{r}^{(i)}, \overline{N} \). Deviation
of the body from the nominal position (vectors \( \Delta \mathbf{R}, \Delta \mathbf{x} \)), reactions \( \mathbf{N}^{(i)} \) in the supporting legs as well as vectors \( \delta \mathbf{r}^{(i)} \) are defined by parameters \( \mathbf{r}^{(i)}, \mathbf{N}^{(i)}, \Lambda^{(i)} \). The values \( \mathbf{r}^{(i)} \), which define the programmed movement of the leg ends, are calculated according to the position control part in the control system. The additional values \( \delta \mathbf{r}^{(i)} \) according to (3.3) are calculated in the force control part of the whole system. Force feedback should be performed with constant coefficients \( \Lambda^{(i)} \). If the programmed movements of the legs (vectors \( \mathbf{r}^{(i)} \)) and the compliance matrix \( \Lambda^{(i)} \) are given, the programmed reaction forces \( \mathbf{N}^{(i)} \), which can be given as an input to the system, uniquely define the support forces \( \mathbf{N}^{(i)} \) and the deviation of the body from the nominal position. According to (3.3), (3.9), (3.10) the actual movement of the robot coincides with the programmed (\( \Delta \mathbf{R} = 0, \Delta \mathbf{x} = 0 \)), if the programmed reaction forces \( \mathbf{N}^{(i)} \) meet the static equilibrium conditions. In this case, the actual reaction forces \( \mathbf{N}^{(i)} \) are identical to the programmed values \( \mathbf{N}^{(i)} \).

To calculate the foot forces, it is necessary to know, in addition to the vehicle weight \( P \), the coordinates \( X, Y \) of the vehicle-centre-of-mass. In most of the known walking vehicles the mass of the legs amounts to a considerable part to the total mass of the vehicle. For this reason coordinates \( X \) and \( Y \) depend on the leg configuration. The calculation of the centre-of-mass in terms of the leg configuration is considered in [2]. At the same place there are presented the algorithms of calculation of the programmed force reactions in (3.3) and experimental results of the force distribution in locomotion over rigid and soft surfaces.

4. 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 linearly depend on the force and torque, the vehicle body will move in accordance with the "accommodation" or "generalised damping" concept [7]. The control law for the position of leg ends \( \mathbf{U}^{(i)} = T^{(i)} G_f (\mathbf{V} - \mathbf{V}_p) \) where \( \mathbf{V} \), \( \mathbf{V}_p \) are measured and commanded values of body velocities, \( T^{(i)} \) is the transformation matrix from axes \( OX, X_1, X_2 \), \( \mathbf{V}_p \) is calculated as

\[
\mathbf{V}_p = G_f (\mathbf{F} - \mathbf{F}_p)
\]

where \( G_f \) - matrix of accommodation. Force vector \( \mathbf{F} \) 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 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.

This approach is demonstrated for two tasks: 1.- insertion of a tube rigidly mounted on the body of the vehicle into a hole of an external object, and 2.- drilling operation with a tool mounted on the body.

4.1. Inserting operation

This approach is demonstrated for insertion of a tube with the diameter \( d_o \) into a hole of an external object. The tube is rigidly connected to the body of a hexapod vehicle (fig. 7) 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 \( d > d_o \).

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 minimised. 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.

The 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 reaction measurements this phenomena is observed as sudden changes of the force components, particularly the changes of the longi-
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 [8]:

$$\overline{V}_p = \overline{V}_n + \overline{V}_t = \lambda \cdot (F - F_n) \cdot \pi + V_c \cdot \overline{L} \tag{4.2}$$

Here $\overline{V}_n$ and $\overline{V}_t$ are the vectors of the outer normal and the tangent with respect to the surface, $\overline{V}_c$ is the programmed value of the tube velocity along the tangent to the surface of the object (contour velocity), $\overline{V}_n$ is the programmed value of the normal component of the contact force to be maintained, $F_n$ is the normal force component, $\lambda > 0$ is a constant. If the friction between tube and surface is absent or known then the vectors $\overline{V}_n$ and $\overline{V}_t$ can be determined from force sensor signals. To use (4.2) in the control system we have to evaluate the value of force $F_n$ and to find vectors $\overline{V}_n$ and $\overline{V}_t$ which describe the directions of the body with the tube.

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 hole $d_h = 65mm$, diameter of the funnel $D = 250mm$, 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 (4.1). 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 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 (4.2).

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

4.2. The force control of vehicles body movement for drilling

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.

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

\[ V_{px} = k_x (F_x - F_{px}) \]
\[ \omega_{py} = -k_y F_y \]
\[ \omega_{pz} = k_z F_z \]
\[ V_{py} = -\omega_{py} R \]
\[ V_{pz} = -\omega_{pz} R \]

where \( V_{px}, V_{py}, V_{pz}, \omega_{py}, \omega_{pz} \) 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, \( F_{px} = \text{const} > 0 \) is the programmed force which has 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.

### 4.3. 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 (4.2). For avoiding jam and tool breakage the control system can compensate for the lateral components of interaction forces which arise during the drilling operation.

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

### Conclusion

- A hexagonal six-legged walking vehicle and its control system that ensures force control in locomotion and body movement have been developed. Main algorithms are 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.

### References