Adaptive Body Motion for Blind Hexapod Robot in a Rough Environment

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Abstract. *In this paper, we address the problem of traversing rough terrains with a hexapod robot. In contrast with other known approaches, we utilise the built-in sensors of the used smart servo drives, which leads to a cheap solution without a need of additional or external sensors. The proposed approach is based on a tactile detection of the ground and proposes a body leveling method that adapts to the terrain being traversed and enables to keep the robot in a suitable configuration with respect to the terrain. By combining the tactile sensing and the body leveling method, we get a smooth and adaptive behavior for our technically blind hexapod walking robot, despite the fact it is. The proposed approach has been experimentally verified in a series of scenarios where a regular motion gait does not allow the robot to traverse the terrain while the proposed method enables a successful gait execution in rough terrains of various difficulty.*

Keywords

Walking robots, hexapod, rough terrain, body motion.

1. Introduction

Walking robots can operate in a much greater scope in terms of terrain diversity than classical wheeled robots, which are usually designed for flat terrain such as office floors, pavements or roads. However, the increased motion capabilities are at the cost of increased control complexity that is caused mainly by the number of controllable degrees of freedom (DOF). Assuming 3 DOFs per leg for a walking robot, we get a total of 18 controllable DOFs for a hexapod robot, which is significantly higher than 2 DOFs in the case of a car-like robot.

One way to handle a high DOF is to generate a walking pattern—a gait [1]. A simple regular gait, where legs follow a predefined trajectory, can be very efficient on flat terrains. In such a gait, we suppose that all legs in the support phase lie on the same plane. Moreover, for a perfect flat surface, it is just enough to rise each leg at the minimal height and move it forward. However, in a case of a rough terrain, the robot needs to traverse small obstacles and a leg can end up at a little bit different height than expected. Then, because the regular gait is designed for a flat terrain, some of the legs can lose the ground support leaving them weaving uselessly in the air and the robot can stuck at that location incapable of moving towards the requested direction. Any single stair is therefore hardly traversable using a simple gait in an open-loop fashion.

The robot motion and its capability to traverse a rough terrain can be increased by closing the control loop and considering sensory information in the generation or execution of the motion gait. There can be find two complementary approaches based on exteroceptive and interoceptive sensors. The exteroceptive sensors such as camera and laser range finder can be used to build an elevation map of the robot surroundings. The map can be then used to estimate the expected stability of the foothold locations [2]. The regularity of foothold positions in a standard motion gait can be also altered according to the determined locations [3]. Notice that in such approaches, either the off-line map of the environment is considered to be available, or the map is created on-line by on-board image processing [4]. However, such a map provides only a rough approximation of the robot's surrounding terrain that can be improved using tactile information [5]. Moreover, the tactile information can be even used for classification of the terrain as it has been shown by the same authors in [6].

Instead of using huge variety of sensors—as can be seen on the BigDog [7] and the LittleDog [8] robots built by Boston Dynamics—, the robot's ability to traverse rough terrain can be achieved by a lot smaller and thus a lot cheaper effort. For example, an additional way how to determine the support level of the legs—beside direct force or contact sensors—can be based on the feedback from the actuators provided by servo drives to prevent overloading. Palankar et al. proposed to utilize an additional passive actuator to read and control the load of the support level [9]. Information provided from the passive actuator is used to determine the joint torques and design the robot motion gaits that are independent on inertial and exteroceptive sensors, while their approach improve motion of a hexapod walking robot in rough terrains. Thus, although the map of the environment is not

available, a local adaptive motion controller can be built on a technically blind robot [10].

In our previous work, we investigated the problem of detecting the level of the support, based on [9], but rather than adding additional passive actuator, we directly rely on the active actuator itself. Thus, we follow a minimalist approach where no additional sensors are required to provide a stable crawling on a rough terrain.

The body motion also plays a big role in the design of a gait. For a legged robot, the center of gravity (COG) needs to be situated inside the support polygon formed by the supportive legs in order to ensure static stability of the gait [11]. A lot of approaches utilise the (partial) knowledge of the terrain and plan each foothold accordingly to this knowledge. The body motion is therefore planned to improve stability, smooth the body trajectory or enlarge reachable areas for particular legs [12]. Since we do not have such terrain knowledge available, we cannot plan a sophisticated body motion. Moreover, we do not have information about tilt angles of the robot; hence we are not able to determine, whether the COG is actually above the support polygon. We propose an adaptive body leveling method, which offers a feasible solution in the case of blind walking with tactile sensing as the only information about the outer world.

The reminder of the paper is organized as follows. A specification of the problem and considered assumptions are presented in Section 2. The proposed method of adaptive body motion is described in Section 3. Experimental results of the proposed method in real environments are reported in Section 4 and concluding remarks in Section 5.

2. Problem Statement

The main problem being addressed in this paper is to handle carefully the body posture of the hexapod robot during the gait execution. Moreover, the problem is studied under the conditions that the robot has no information about the outer environment except the actual servo positions. In particular, we consider the PhantomX Hexapod Mark II robot equipped with Dynamixel AX-12A actuators, which represents a relatively cheap and easy-to-use platform. This platform is well suited for flat terrain operations with a regular gait without any feedback from its own motion. Nevertheless, it has the potential to evolve from a six-legged oscillator into a reactive autonomous agent by exploiting its capabilities using only the feedback from the servos.

As the robot is completely blind, we consider the pentapod gait with one leg moving at a time, which increases the gait stability in a rough terrain [13]. The gait diagram is shown in Fig. 1, where the motion strategy (highlighted blocks) and computation steps (non-highlighted blocks) during each leg cycle are presented. The legs are alternating in a ripple gait with a given order: LF—RR—LM—RF—
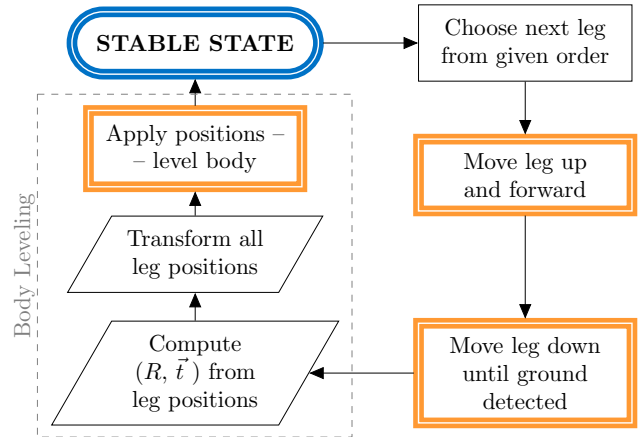

Fig. 1. Gait diagram. After the leg reaches ground, the transformation parameters are computed in order to get more suitable robot body posture. R and $\vec{t}$ denote the robot rotation matrix and translation vector, respectively.

LR—RM[1]. The active leg leaves its foothold, moves forward, and begins approaching the ground. During the depression phase, the data from its actuators are analyzed for a possible ground contact. When a ground is detected, the leg stops with the depressing and the body position and rotation is then adjusted to better suit with the new configuration of the feet.

2.1. Hexapod Structure

The used hexapod platform has six legs—each with three joints formed from the Dynamixel actuators. The schema of the leg and the description of its parts is depicted in Fig. 2. The construction of the robot allows to traverse small obstacles, but of course of a limited size due to the dimensions of the legs and robot itself. Regarding the surface detection method, we consider the robot is operating in a rough environment that satisfies the robot's construction limits and there is not a large obstacle that the robot cannot traverse. In a case of large obstacles, we consider a rough map of the terrain can be created, e.g., using camera or laser sensor, for a high level planning to find a traversable terrain similarly as in [3]. Thus, in this paper, we focused on the local motion control and on-line adaptation of the motion gait based on the tactile sensing of the terrain.

3. Body Leveling Method

After a leg changed its foothold, the static stability properties of the robot changed too. Because the actual foothold positions vary a lot with the challenging terrain beneath the robot and we do not know the resulting foothold of a moving leg beforehand, a particular leg can move close to the border of its operating space. Therefore, the body has

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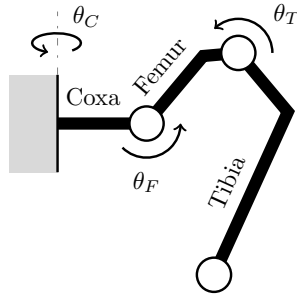[1] LF = left-front, RR = right-rear, LM = left-middle, etc.

Fig. 2. Schema of the leg consisting of three parts (links)—Coxa, Femur and Tibia. The three joints (θ_C, θ_F, and θ_T) are indexed according to the next respective link. The joint θ_C is fixed to the body with a vertical rotation axis while the other two joints have a horizontal rotation axis.
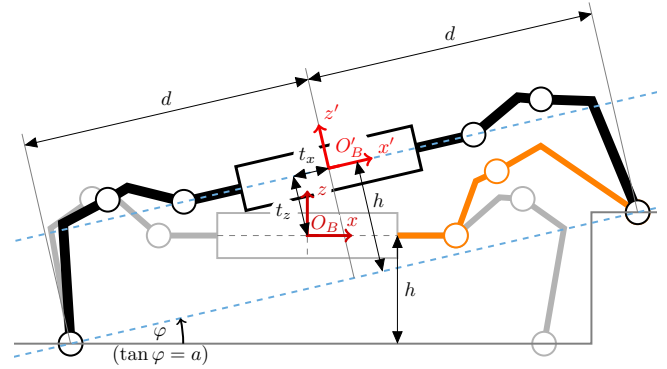

Fig. 3. Simplified schema of the body leveling. When a leg (right gray) reaches new foothold (orange), the body posture is adjusted by changing the configuration of the legs (black) while keeping the same distances h and d.

to counteract these changes by shifting and rotating into a more suitable position to improve the stability and leg working space margins.

An optimal body posture[2] can be very hard to find considering all DOFs because each body posture offers different possibilities of the movement depending on how close to the working space limits the legs are. The reachable areas of legs can be optimized by a specific body motion in order to obtain better initial conditions for the next swing leg as was studied thoroughly in [12] for a quadruped robot; however, the motion planning algorithm benefits from a terrain elevation map, which is not available in our approach. Since the robot has to walk over a rough terrain without any perception about the terrain ahead, there is no option to choose any preferable body posture in order to prepare for the oncoming terrain. Therefore, there has to exist an *equilibrium body posture*, which offers balanced possibilities of the movement in all directions. Such posture also needs to reflect the changes in the terrain structure such as oncoming inclined plane or stairs that—combined with the absence of an inclinometer—can yield in an awkward body posture if not carefully handled.

Since the body has no actuator itself, the foot positions has to be transformed instead. Assuming that all legs lay on the ground, applying their new positions will enforce the body to move while the legs keep their footholds. The body movement can be represented in the form of a transformation of the body coordinates as

$$\begin{bmatrix} x'_B \\ y'_B \\ z'_B \\ 1 \end{bmatrix} = \begin{bmatrix} R & R\vec{t} \\ 0\,0\,0 & 1 \end{bmatrix} \begin{bmatrix} x_B \\ y_B \\ z_B \\ 1 \end{bmatrix} \quad (1)$$

or in the form of an inverse transformation of the foot coordinates as

$$\begin{bmatrix} x'_i \\ y'_i \\ z'_i \\ 1 \end{bmatrix} = \begin{bmatrix} R^T & -\vec{t} \\ 0\,0\,0 & 1 \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ z_i \\ 1 \end{bmatrix}, \quad (2)$$

which can be separated into two steps as follows:

Firstly, we have to rotate the body using rotation matrix R to adapt to the new foothold positions. It is obvious that the new foot positions have to keep the same distances between each other as the old ones, which is preserved when the rotation matrix R is orthonormal. For this purpose, we use a simple linear regression. Having the foot positions[3], we can determine parameters a, b, and c of the plane (with the equation $z = ax + by + c$) that fits the foot positions, i.e., their squared distance from that plane is minimized. Then, the new body position is transformed to be parallel with this plane as it is depicted by dashed blue lines in Fig. 3.

Secondly, we have to shift the rotated body to improve stability and leg working space margins. We can average the foot positions to get their "center", which we consider as the *equilibrium body position*. Note that we are considering only the x and y coordinates of the new rotated plane. The new body $[x, y]$ position can therefore be expressed as the average of the rotated foot $[x, y]$ positions. The body height (z coordinate) is then adapted to keep the body at the default height 0.1 m above the estimated plane. The x and z projections of the translation vector $\vec{t}$ are shown in Fig. 3 as t_x and t_z.

Notice, that the translation is preceded by the rotation. Hence, the translation vector $\vec{t}$ is multiplied by the rotation matrix R as can be seen in (1). This convention follows the logic of compensating the body position offset in the newly computed approximate plane and also helps to simplify future equations.

The *apply positions* block in Fig. 1 can be directly performed by solving the rotation and translation separately and applying the resulting matrix R and vector $\vec{t}$ into (2). A fundamental schema of the body leveling method considering only two legs is shown in Fig. 3.

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[2]The body posture is meant in a 6D space containing both position and orientation

[3]The world coordinate system xyz is oriented as follows: z-axis is pointing vertically upwards, the x-axis is heading in the robot's forward direction and the y-axis is pointing to the left; hence, they form the right-handed coordinate system.

3.1. Rotation

The rotation matrix can be created by setting up its basic vectors individually. For a better readability, we create an orthogonal (not orthonormal) basis $\begin{bmatrix} \vec{b}_x & \vec{b}_y & \vec{b}_z \end{bmatrix}$ first, and norm its vectors later.

Since we need to preserve the forward walking direction, the first basic vector $\vec{b}_x$ can be formed directly using the parameter a from the regression plane as $\vec{b}_x = \begin{bmatrix} 1 & 0 & a \end{bmatrix}^T$. The parameter a represents the $pitch$ angle here.

Becaues the third basic vector $\vec{b}_z$ is heading upward and is perpendicular to the regression plane, it can be obtained directly from its general form $0 = ax + by - z + c$. Hence, we get $\vec{b}_z = \begin{bmatrix} -a & -b & 1 \end{bmatrix}^T$.

The last basic vector is simply any vector that is linearly independent. Such a vector that completes an orthogonal basis is $\vec{b}_y = \begin{bmatrix} -ab & a^2 + 1 & b \end{bmatrix}^T$.

The resulting orthonormal rotation matrix R is then created from the basic vectors of the orthogonal matrix dividing them by their norms as follows

$$R = \begin{bmatrix} 1 & -ab & -a \\ 0 & a^2+1 & -b \\ a & b & 1 \end{bmatrix} \begin{bmatrix} ||\vec{b}_x|| & 0 & 0 \\ 0 & ||\vec{b}_y|| & 0 \\ 0 & 0 & ||\vec{b}_z|| \end{bmatrix}^{-1}. \quad (3)$$

3.2. Translation

The translation vector can be expressed by rewriting (2) line by line as follows

$$x'_i = \frac{\vec{b}_x \begin{bmatrix} x_i & y_i & z_i \end{bmatrix}}{||\vec{b}_x||} - t_x \quad (4)$$

$$y'_i = \frac{\vec{b}_y \begin{bmatrix} x_i & y_i & z_i \end{bmatrix}}{||\vec{b}_y||} - t_y \quad (5)$$

$$z'_i = \frac{\vec{b}_z \begin{bmatrix} x_i & y_i & z_i \end{bmatrix}}{||\vec{b}_z||} - t_z \quad (6)$$

Note that the $[x', y']$ coordinates are the new foot positions that are designed in a way that the body $[x, y]$ position is computed from their average. Hence, we know that $\sum_{i=1}^{6} x'_i = 0$ and $\sum_{i=1}^{6} y'_i = 0$. From the sum of (4) and (5) over all six legs, we can directly express the parameters t_x and t_y.

The last coordinate of the translation vector $\vec{t}$ has to compensate the change in the body height h above the ground. It can be computed easily using the similarity of triangles as $\frac{1}{||\vec{b}_z||} = \frac{t_z - h}{c}$. The translation vector is therefore

$$\vec{t} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} = \begin{bmatrix} \frac{\sum x_i + a \sum z_i}{6||\vec{b}_x||} \\ \frac{-ab \sum x_i + (a^2+1) \sum y_i + b \sum z_i}{6||\vec{b}_y||} \\ \frac{c}{||\vec{b}_z||} - h \end{bmatrix}. \quad (7)$$

By applying the transformation of all leg coordinates from (2) and executing the motion to get the legs to their new positions, we achieve the body to move. Since the legs are always moving a bit forward—though the distance between the new and old foot positions is variable—and the body position is computed as an average of the foot positions, the body is therefore following the legs, no matter which leg or how far the leg is moving. This small moves ensure the whole body movement and thus the movement of the whole robot.

4. Experimental Results

The proposed adaptive body leveling method supported by the tactile sensing of the ground has been verified in a series of experimental scenarios. Firstly, a flat floor has been considered to ensure that there is not a significant drop in the robot's ability to traverse a simple terrain. Then, we consider three scenarios containing rough terrain which the robot is unable to traverse by the default gait although all of the scenarios were prepared with respect to the dimensions of the hexapod.

Although the body position is handled by the leveling algorithm during the gait execution, which is described in the previous section, a constant position offset can be set before an experiment. Therefore, we moved slightly the body position forward in the case of inclined plane and stairs. This setting helps to improve the static stability of the robot and could be set automatically using a tilt information, which is not available in our experiments.

The scenarios are depicted in Fig. 4 and it consists of the inclined plane, stairs and a set of blocks with various height. The developed adaptive motion gait using the proposed body leveling method allows the robot to traverse all the terrains smoothly and the particular performance of the robot has been as follows:

1. The inclined plane scenarios shown in Fig. 4a does not provide significant difficulties to traverse the breaking point even for a slope greater than $20°$. An example of the motion is captured in Fig. 5. Although the sloped terrain (made of wood) is a bit slippery for our robot, the adaptive motion gait helps to avoid lifting the robot body on the swinging leg, which happens in the default gait and which accidentally yields in a loss of support of

(a) Inclined plane (10° / 20° slope)   (b) Stairs (4 cm height)   (c) 10×10 cm blocks of variable height 3–15 cm
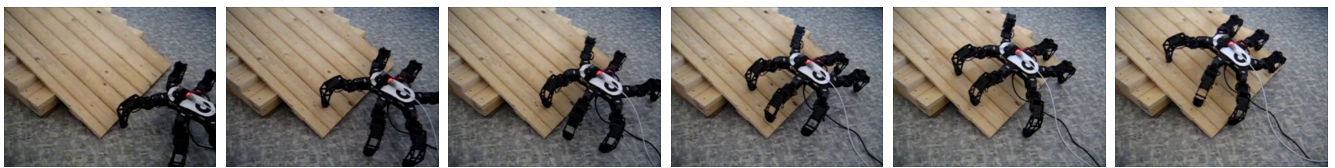
Fig. 4.   Testing scenarios

Fig. 5.   Hexapod traversing an inclined plane

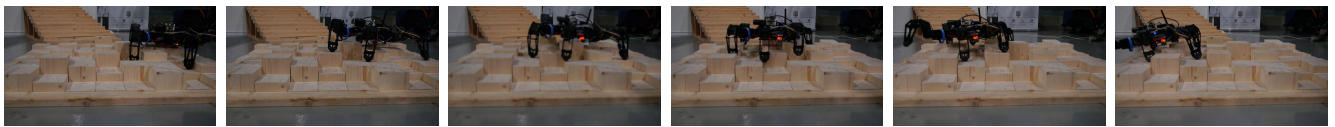**Fig. 6.**   Hexapod traversing stairs

Fig. 7.   Hexapod traversing wooden blocks

several legs and thus sliding the legs down the inclined plane. However, it cannot be avoided at all and small slippages occasionally happen. On the other hand, the robot with the regular motion gait remained stuck at the edge of the inclined plane with no further progress despite the continuous gait execution, which has been observed even for a slightly inclined plane, i.e., about 10°.

2. In the next scenario shown in Fig. 4b, the robot has been able to successfully climb up the stairs. The terrain is more challenging because the stairs provide less feasible footholds than a simple plane, and edges of the stairs are particularly difficult for the robot. Though, the occurrence of a slippage is less likely to appear due to the horizontal surface of each stair. The main issue in this scenario has been observed when the robot stepped on an edge. Although it did not cause a downfall immediately, the foot fell one step down when the leg became more loaded due to the other legs movement. This case resulted in a slight loss of the stability with several legs hanging in the air (the robot has always support of at

least three legs, naturally). Although such an accident is not avoidable because the robot is technically blind, the robot is able to regain its lost stability within a few following steps due to the adaptive behavior of the gait. Soon or later, the robot has a five-leg support again.

3. Finally, in the last scenario shown in Fig. 4c, the robot exhibits a similar behavior as for the stairs scenario and it is able to successfully traverse the wooden blocks repeatably. The only issue is related to the height of the blocks, where the tallest blocks cannot be just next to the lowest ones because the robot is physically incapable to traverse such obstacles due to the length of its legs.

5. Conclusion

We propose a method to handle the body motion that optimizes the stability and leg working space properties during the gait execution. The method is employed in an adap-

tive motion gait—based on a tactile ground detection—that allows a blind hexapod walking robot to traverse rough terrain using a pentapod gait.

The proposed approach does not rely on any additional sensors and thus its main benefit is in easy deployment of cheap platforms that are basically composed only from a body, legs, and servo drives.

Although the proposed approach does not provide motion capabilities for challenging rough terrains, it enhances the robot motion that is basically limited to flat surfaces only. Thus, we believe the proposed adaptive gait enables deployment of cheap hexapod walking robots in further research and applications.

Acknowledgements

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