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Body Levelling of a Hexapod Robot using the Concept of Sensor Fusion

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Abstract—Contrary to their wheeled counterpart, multi-legged robots are capable of easily changing their body posture through reconfiguration of the legs (i.e. inclination or posture control). This capability is exploited in the paper at hand to level out a six-legged robot when placed on a plain slope with adjustable inclination. By extension such inclination control could then be used to let the legged robot mount plain slopes with its body horizontally which greatly benefits the way the robot absorbs the load posed on its mechanics. The implemented body levelling algorithm uses the hexapod's forward and inverse kinematic model, basic geometry, and the Cartesian plane equation to calculate the leg tip displacements able of counteracting the fused orientation data obtained from an inertial measurement unit (IMU). Experimental results show the approach to be successful, although the speed of the levelling process leaves room for improvement. To address the latter a more powerful processing unit and/or, more importantly, a simpler redesign of the legs is advised.

I. INTRODUCTION

Spurred by enormous improvements in actuation, sensing and computing capabilities, the field of robotics has flourished tremendously over the past few decades. Besides the traditional robot manipulator arms which have already reached a high state of maturity, considerate attention is being spent to the creation of mobile robots and gifting these with ever higher degrees of autonomy. One such type of mobile robots being the target of countless studies is the six-legged or hexapod robot. This insect-like machine possesses great stability properties and as such shows great promise for use in applications where rough, unstructured terrain has to be traversed like search and rescue operations in the wake of natural disaster [1], [2], volcanic and/or extraterrestrial exploration [3], mountain logging [4], maintenance and repair of societal centric structures [5], mine clearance [6] etc.

Contrary to their wheeled counterpart, multi-legged robots have the desirable ability to adjust their body configuration while moving (e.g. reposition their centre of gravity, change body orientation) [7]. Just as the legendary mountain goat-like animal Dahu which has legs of different lengths to fit the mountain side, a hexapod robot should also be able to adjust its legs in order to mount slopes more instinctively. It can easily be shown profitable from a mechanical point of view

since levelling the hexapod on a slope avoids the occurrence of an extra moment onto the body of the bug-like creature.

Towards achieving this levelling, the robot should have an actual sense of how its body is oriented on the slope. In this paper the use of an inertial measurement unit (IMU) is opted for which combines accelerometers, gyroscopes and optionally digital compasses to get highly accurate estimates on the body's orientation. Therefore an IMU can be seen as the embodiment of the concept of sensor fusion which is a major and extensively examined research topic. As described by Dudek and Jenkin [8] sensor fusion is about combining measurement data from different sensors, positions and/or times to obtain better measurement estimates than when these sources were used individually. One other example in mobile robotics where sensor fusion techniques prove particularly useful is the process of maintaining an ongoing estimate of the position of a robot relative to some external set of landmarks or features [9]. Although various approaches have been developed to guide the process of sensor fusion, two distinct but related techniques have become pre-eminent in mobile robotics, namely approaches based on the classic least squares combination of estimates (Kalman filter, extended Kalman filter) and approaches that utilize a less strong error model (Markov localisation, discrete grid representations, Monte Carlo and condensation techniques) [8].

The paper at hand covers the implementation of a body levelling algorithm for a hexapod robot using an inertial measurement unit. In what follows, section II and III first describe the six-legged robot and the sensor fusion used to perform the body levelling experiments. Next, in section IV the forward and inverse kinematic model are discussed to gain insight into the relationship between joint actuation and actual leg tip displacement. The algorithm to let the hexapod level out its body horizontally on plain slopes of up to ten degrees inclination is given in section V. The experimental results are presented in section VI while the conclusions are given in section VII.

II. SYSTEM DESCRIPTION

The experiments are done using a six-legged robot with a traditional inline design (Fig. 1). Each of the six legs is equipped with two Standard Futaba S-3111 servos enabling a forward/backward hip swing and an up/down leg lift (two degrees of freedom per leg). These servos only use position sensing via a potentiometer as an elementary part of their working principle; the position measurement itself is not made available to the user ruling out the implementation of any form of feedback control. It should also be noted that using only two degrees of freedom (DOFs) per leg evidently poses constraints on the maximally attainable manoeuvrability (e.g. no sideways walking possible, less flexibility in overcoming certain obstacles).

Fig. 1. The hexapod robot used to perform the body levelling experiments.

Furthermore, the robot is equipped with an Invensense MPU-6050 inertial measurement unit (IMU) which combines a three-axis accelerometer (yielding acceleration along three perpendicular axes) and three-axis gyroscope (furnishing the angular speed about each of the axes) together with an on-board digital motion processor (DMP). This sensor is discussed more thoroughly in section III.

As for the computational unit of the robot, a single-board embedded computer with an AM335x 1GHz ARM Cortex-A8 processor and 512MB DDR3 RAM, called BeagleBone Black (BBB), was chosen. This BBB is light, low in energy consumption and should be powerful enough to do all of the necessary computations. Unfortunately, the BBB is not capable of delivering twelve PWM signals at a time. This implies that the servo-actuated leg joints cannot be controlled individually which would decrease the degree of flexibility. To cope with this the Mini Maestro 12-channel USB servo controller has been used. A full schematic representation of the hardware components is given in figure 2. Note that the hexapod robot was part of a larger project on developing autonomous robot for environmental exploration [10] and therefore the hardware contain sensors (e.g. stereo vision, ultrasonic) which are not relevant for the scope of this paper.

III. IMU SENSOR FUSION

The procurement of highly accurate estimates of the body's orientation is an absolute prerequisite for the success of the levelling algorithm. To achieve this, accelero and gyroscope

data (and optionally digital compass data) - which are quite complementary - are often used together in sensor fusion. As mentioned before the IMU used here combines a triple axis accelerometer and gyroscope and is mounted centrally on the hexapod robot. By placing the IMU like this, the roll or longitudinal axis is equal to the y-axis, the pitch or transverse axis corresponds to the x-axis and the yaw or normal axis is equivalent to the z-axis.

The gyroscope delivers angular velocity about a particular axis (x, y and/or z) and thus needs to be integrated once to deliver the changes in rotational attributes of a body like pitch, roll and yaw. Using the accelero data, it is also possible to calculate the Euler angles pitch θ and roll ϕ in rather static applications by looking at the decomposition of the gravity vector along the three axes (x,y,z) and applying the following trigonometric relations:

$$\theta = \arctan \frac{a_Y}{\sqrt{a_Z^2 + a_X^2}} \quad (1)$$

$$\phi = \arctan \frac{a_X}{\sqrt{a_Y^2 + a_Z^2}} \quad (2)$$

The yaw on the other hand, cannot be computed using the accelerometer data due to the fact that turning around the yaw axis does not cause any change in the accelerations, e.g. a strict rotation around the yaw axis will cause accelerations a_X and a_Y to remain zero, while a_Z stays equal to the gravitational acceleration g .

As becomes clear from the discussion above both accelerometers and gyroscopes can, after some processing, grant information on the orientation of the robot's body. As it happens, both sensors have got their own distinct drawbacks and advantages making them perfectly suited for applying the concept of sensor fusion. On the one hand accelerometers are very noisy (e.g. most of the time a low-pass filter is applied causing a delayed response) but remain stable over time. Gyroscopes on the other hand are very smooth (as a result of the single integration of the angular velocity over time) with a fast response, but unfortunately the integration also instigates an inevitable drift over the long run. Moreover the gyro does not measure the gravity vector while it is desired to perceive the tilt w.r.t. this vector as is luckily done by the accelerometers. Consequently, the accelero and gyro data are indeed often combined to get enhanced results. The accelerometer corrects the gyro for drift and maintains the orientation w.r.t. gravity and the gyro ensures a fast, more smoothed response. The fusion itself is often done by a Kalman or a complementary filter. However, not being able to calculate the yaw with the accelerometers makes the drift correction for this angle not as well as for the pitch and roll values.

The MPU-6050 has an on-board DMP which is able to do a nine-axis sensor fusion between three-axis gyroscopes, accelerometers and optionally also compasses. In theory, if one really wants to be able to correct the long term drift of the yaw as well, this latter three-axis compass should be able to provide the solution by delivering the magnetic north to the

Fig. 2. Full schematic of the various hexapod robot's components and their interfacing.

gyroscopes. Although, even without the implementation of the compasses, the data processed by the DMP gives quite accurate yaw values due to the Invensense motion determination [11]. This algorithm is used to determine whether a sensor, that can identify motion (e.g. gyroscopes and accelerometers), has moved or not. Basically, when a signal is received from the sensor, the moments of this signal are calculated and compared to determine whether the signal is Gaussian. If so, it is recognised as coming from a non-moving sensor while a non-Gaussian one implies an event of motion.

IV. KINEMATIC MODEL

In order to level out the hexapod's body when placed on a slope, the six-legged creature should be able to actuate its legs such that they counteract the body orientation measured by the IMU. Such leg movement requires a proper understanding of the relationship between the servo-actuated joint rotations and the corresponding leg tip displacement. To this end, a forward and inverse kinematic model is derived.

A. Forward kinematics

Fig. 3 shows the rod mechanism of the legs in a sketch of the rear side of the hexapod robot. A simplified leg model (of the left rear leg) is also depicted in Fig. 4 serving as a guide for the derivation of the forward kinematics and inverse kinematics. The origin of coordinate frame (v,w) is placed at the shaft of the knee servo and the origin of coordinate frame (x,y,z) is located on top of the frame at the hip joint.

Firstly, the forward kinematics are calculated in order to find out the end effector position H when the servo angles (i.e. the knee angle θ and the hip angle ϕ) are given. By means of example the derivation is done for the left rear leg. Starting from the knee servo motor a basic rotational movement θ

determines the coordinates of point B with respect to the (v,w) -coordinate frame:

$$\begin{cases} v_B = |AB|\cos\theta \\ w_B = |AB|\sin\theta \end{cases} \quad (3)$$

In order to obtain the (v_C, w_C) -coordinates and the angles ψ and α , the following equation are employed:

$$\begin{cases} v_C = |AB|\cos\theta - |BC|\cos\alpha \\ w_C = |AB|\sin\theta - |BC|\sin\alpha \\ v_C = v_D + |DC|\cos\psi \\ w_C = w_D + |DC|\sin\psi \end{cases} \quad (4)$$

To determine the coordinates of the end effector point H with respect to the (v,w) -reference frame, we made use of the next trigonometric equations:

$$\beta = \psi - \tan^{-1} \frac{|IC|}{|ID|} \quad (5)$$

$$\begin{cases} v_F = v_D + |FD|\cos\beta \\ w_F = w_D + |FD|\sin\beta \end{cases} \quad (6)$$

Fig. 3. Rear view of the hexapod robot.

Fig. 4. Rod mechanism representation of a left leg.

$$\begin{cases} v_G = v_E + |EG|\cos\beta \\ w_G = w_E + |EG|\sin\beta \end{cases} \quad (7)$$

$$\begin{cases} v_H = v_G - |GH|\sin 5^\circ \\ w_H = w_G - |GH|\cos 5^\circ \end{cases} \quad (8)$$

In order to know the 3D position of the foot, the hip swing effect needs to be taken into account as well. Therefore, the (v_H, w_H) -coordinates are described with respect to the (x, y, z) -coordinate frame:

$$\begin{cases} x_H = (v_H - 30)\cos\phi \\ y_H = w_H - 40 \\ z_H = -x_H\tan\phi \end{cases} \quad (9)$$

This merely implies a translation over the fixed distances (30 mm in x-direction and 40 mm in y-direction) between the two coordinate frames and a rotation depending on the hip angle ϕ as in Fig. 5.

B. Inverse kinematics

After obtaining the forward kinematics, the inverse kinematics are determined based on Fig. 4 and 5 such that a wanted end effector position can be translated into actual actuator angles (knee angle θ and hip angle ϕ). Notice that there are only two degrees of freedom; as such the end effector (y_H, z_H) -coordinates form sufficient input for the inverse kinematic model to find the corresponding servo angles. First of all, the angle β is calculated starting with the known y-coordinate of the end effector H:

$$\begin{cases} w_H = y_H + 40 \text{ mm} \\ w_G = w_H + |GH|\cos 5^\circ \\ \beta = 180^\circ - \arcsin \frac{w_G - w_E}{|EG|} \end{cases} \quad (10)$$

The value of β is then used to determine v_H and ψ using:

Fig. 5. Top view of the hexapod robot.

$$v_H = y_E + |EG|\cos\beta - |GH|\sin 5^\circ \quad (11)$$

$$\psi = \beta + \arctan \frac{|IC|}{|ID|} \quad (12)$$

Once ψ is known, we can calculate the coordinates of the point C with respect to the (v, w) -frame using next equations:

$$\begin{cases} v_C = v_D + |DC|\cos\psi \\ w_C = w_D + |DC|\sin\psi \end{cases} \quad (13)$$

Then the angles δ and γ (Fig. 4) are calculated using the coordinates (v_C, w_C) and trigonometric relationships:

$$\begin{cases} |AC| = \sqrt{v_C^2 + w_C^2} \\ \delta = \arctan \frac{w_C}{v_C} \\ \gamma = \arccos \frac{|BC|^2 - |AB|^2 - |AC|^2}{-2|AB||AC|} \end{cases} \quad (14)$$

At last, all of the acquired information is combined in order to compute the corresponding knee and hip servo angles (i.e. θ and ϕ):

$$\begin{cases} L = v_H - 30 \text{ mm} \\ \phi = -\arcsin \frac{z_H}{L} \\ \theta = 180^\circ + \gamma + \delta \end{cases} \quad (15)$$

Note that the forward and inverse kinematics of the right legs can be acquired by similar reasoning.

V. BODY LEVELLING

Depending on the situation at hand multiple different leg configurations could be applied to counteract the roll and pitch values measured by the IMU. Therefore, some constraints need to be imposed. First of all the levelling procedure starts with the current hip angles as a fixed given. Although this decreases the flexibility of overcoming a steeper slope, it reduces the levelling options by a certain amount along

with the complexity of the algorithm. Secondly, the algorithm begins by checking which leg is positioned lowest onto the slope (i.e. evaluating the signs of the measured pitch and roll). Once the robot knows which leg is situated most downhill, it starts with extending this leg to its maximum limit, thus choosing the minimal reachable y-coordinate known from the kinematic study in section IV. Together with the constraints imposed on the hip angles mentioned earlier, the downhill leg's actuators are completely determined. For the further explanation of the algorithm let us consider that LF (left front leg) is fully extended.

The next steps in the algorithm define the plane in which the feet of the hexapod should be put in order to counteract the measured pitch and roll. Since a plane can be defined with only three points, besides LF only two other leg tip positions need to be identified. RF (right front leg) is chosen such that the height difference between the RF and LF leg tips compensates the measured roll (Fig. 6(a)), and similarly, LR (left rear leg) such that the LF and LR height difference compensates pitch (Fig. 6(b)). Following this reasoning we have:

$$\tan \alpha = \frac{y_{LF,H} - y_{RF,H}}{x_{RF,H} + 177 - x_{LF,H}} \quad (16)$$

$$x_{RF,H} = (v_{RF,H} + 30)\cos\phi = \dots = f(y_{RF,H}) \quad (17)$$

$$\begin{aligned} \tan \lambda &= \frac{y_{LR,H} - y_{LF,H}}{-z_{LF,H} + 272 + z_{LR,H}} \\ &= \frac{y_{LR,H} - y_{LF,H}}{-z_{LF,H} + 272 + f(y_{LR,H})} \end{aligned} \quad (18)$$

where $x_{RF,H}$ refers to the x-position of the right front end effector (i.e. leg tip) with respect to the fixed hip coordinate frame, $v_{RF,H}$ is the same but with respect to the rotatable knee frame, and ϕ is the known hip angle.

Finally these three leg tip positions are transformed to one common coordinate frame enabling the expression of the plane in its Cartesian equation ($ax+by+cz=d$). Now the robot is able to redirect the remaining legs to fit the calculated plane. For example, for RM (right middle leg) this is done by solving a set of three equations, namely the Cartesian equation, $x_{RM,H} = f(z_{RM,H})$ and $x_{RM,H} = f(y_{RM,H})$ (obtained from the inverse kinematics).

VI. RESULTS

To provide proof of concept the six-legged robot is placed randomly (i.e. random yaw value) on a plain slope of which the inclination can be adjusted. Due to physical limitations imposed by the robot design the maximum inclination that can be dealt with is about 10° . When placed on the slope the deviation from the desired horizontal body orientation (zero pitch and roll) is detected using the IMU and the body levelling algorithm starts. Figures 7-8 show two measurements obtained for a slope with an inclination of 7.6° . During the first few seconds (about 4 s), the system computes the servo

Fig. 6. Body levelling principles.

positions necessary to counteract the observed inclination. Once these are obtained, the servo commands are sent out and the hexapod readjusts its configuration. This process is repeated until the measured pitch and roll values lie within a predefined region around the desired 0° -orientation ($\pm 0.3^\circ$ for Fig. 7 and $\pm 0.035^\circ$ for Fig. 8).

In Fig. 7 the robot is placed on the slope such that the initial pitch and roll deviation are about 3.8° and -6° respectively. It takes two iterations over a time of 6 s to reach the desired horizontal body orientation. The small offset that remains is due to the chosen boundary width of the region around the 0° -orientation. In Fig. 8 the hexapod is placed differently on the slope and the predefined convergence boundaries are chosen to be stricter ($\pm 0.035^\circ$ instead of $\pm 0.3^\circ$) such that the offset is minimised. Now it takes about 20 seconds and several steps to reach the horizontal body pose, but the steady-state error has been reduced significantly.

The results show that the algorithm is successful in levelling the hexapod's body horizontally, however it is rather slow in doing so. This lack of speed is caused by the fact that the computations needed to solve the kinematic model corresponding to the given hexapod design are quite demanding (e.g. nonlinear solvers) in light of the limited computational capabilities of the single-board embedded computer (BBB). Moreover in all the cases it takes multiple steps to reach the horizontal orientation. Besides by the influence of the predefined convergence boundaries and wrongly measured

Fig. 7. Body levelling when placed on a slope with 7.6° inclination. Initial pitch and roll deviation of about 3.8° and -6° respectively. Convergence boundaries set equal to $\pm 0.3^\circ$.

Fig. 8. Body levelling when placed on a slope with 7.6° inclination. High initial pitch deviation. Stricter predefined region of convergence, namely $\pm 0.035^\circ$ instead of $\pm 0.3^\circ$.

model parameters, this can be explained by the absence of a local controller for each servo. As the higher level control calculates the wanted servo angles there is no lower level control which ensures that these are really obtained. Therefore, a more powerful processing unit and the addition of local controllers for each joint servo will probably deliver even more satisfying results.

VII. CONCLUSIONS

In this paper an algorithm to level a hexapod robot placed on a plain slope is proposed. The algorithm involves the use of the robot's kinematic model and some geometric relationships to calculate how the leg tips should be redirected in a plane able of counteracting the orientation angles (i.e. pitch and roll) measured by an inertial measurement unit. Experiments prove

to be successful but the computations needed to solve the kinematic model of the hexapod robot are quite demanding for the single-board embedded computer, resulting in a rather slow response. Besides the obvious use of a more powerful processing unit, a simpler redesign of the hexapod's leg configuration (i.e. abandoning the leg lift mechanism implemented in the current design and using three degrees of freedom) could greatly speed up the levelling process. This conclusion stresses the importance of the design phase in the realisation of any application.

In a next step, the implemented inclination control could now be used to let the robot mount slopes with its body horizontally which is highly profitable from a mechanical point of view. However, the suggested approach is limited to fairly even slopes due to its reliance on the Cartesian plane equation so when rougher, more irregular slopes have to be overcome another method should be adopted (e.g. extend the sensory system with 3D force sensors in each of the legs).

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