Biomimetic Design and Development of a Hexapedal Running Robot with Automatic Gaiting Selection Based on Terrain

Ma Tien Choon
Centre of Artificial Intelligence and Robotics (CAIRO)
Faculty of Electrical Engineering, Universiti Teknologi Malaysia
81310 Skudai, Johor, Malaysia.
Tel: +607-5535793, E-mail: tienchoon@yahoo.com

Shamsudin H.M.Amin
[2]Centre of Artificial Intelligence and Robotics (CAIRO)
Faculty of Electrical Engineering, Universiti Teknologi Malaysia
81310 Skudai, Johor, Malaysia.
Tel: +607-5535319, E-mail: sham@fke.utm.my

Abstract

Animals inspire our intuition that legs may be necessary for satisfactory exploration of highly broken and unstable landscapes. Gaiting style is the next crucial element in determining mobility of the legged robot as special gaits improve the mobility of the robot drastically and permit the robot to climb over small obstacles or cross broken terrain more efficiently. The aim for this research is to design and develop an automatic gaiting selection system which decides the gaits of the robot according to the environments using embedded vision system. The proposed method has been tested on the Hexapedal Running Robot and result is discussed in this paper.

Keywords:

robotics, vision, image processing, legged robot.

Introduction

Much recent interest in the field of walking and running robots has been placed on the adoption of principles found in animal locomotion. Dynamic locomotion in animals has also received significant attention as they exhibit a robust and fast navigation platform. For example, Raibert's pioneering work made use of symmetry in running for the design of bouncing monopods [1].

Legged robots offer superior mobility over natural terrain as well as greater versatility in functionality than traditional mobile platforms [2]. However, it turns out to be difficult to fully realize this potential and create a legged machine that is capable of facing real world challenges [3].

RHex is a prototype built on biological principles similar to the ones described here also demonstrates the possibility of simple, robust dynamic running machines [4]. Based on the finding that legged animals with diverse morphologies all operate as spring-mass systems, these engineers have developed a revolutionary approach to control a robot with many legs, joints and actuators (many degrees of freedom) [5]. Another example is the robot built by Center for Design Research, Stanford University, California named "Sprawlita". Stanford has developed the novel capability to build flexible structures with embedded sensors and actuators that will revolutionize the design of robotic parts [6].

In essence, fast robust locomotion appears to be the result of the dynamic interaction between sprawled posture, a timed feed forward motor controller [7][8], and well-tuned passive visco-elastic elements, also known as "preflexes" [8]. This is in contrast to the control schemes of many robots, which rely heavily on active feedback control rather than passive components [7].

There are many examples in the literature of simple computer vision algorithms proving to be extremely useful in a variety of applications [9] [10] [11] [12] [13]. However the usefulness of these algorithms is often limited by the cost and complexity of the hardware needed to implement them. Such systems traditionally consist of a camera, a frame grabber, and an associated computer to interface to the frame grabber and execute the algorithm [9].

Recent hardware developments now make it possible to greatly simplify and reduce the cost of these systems. The two developments which can take advantage of in this work are low cost CMOS color camera modules and high speed, low cost microcontrollers. A major advantage of CMOS versus CCD camera technology is the ability to integrate additional circuitry on the same die as the sensor itself [14]. This makes it possible to integrate the analog to digital converters and associated pixel grabbing circuitry so a separate frame grabber is not needed [14].

As microcontrollers have become more prevalent their cost has decreased and their capabilities have increased [15]. This makes it possible to perform simple pixel processing on the fly as the pixel values are scanned out of the camera making a full frame become unnecessary in many situations [10]. This suggests that it should be possible to team a

CMOS camera chip with a low cost microcontroller and implement a simple vision system [16].

'Gait' means a pattern of discrete foot placements performed in a given sequence [17]. Biological organisms use an interesting and varied set of motion patterns, or gaits, to move themselves through their environment [18]. In fact, many organisms choose from a selection of gaits, depending on several parameters, including the gait's appropriateness for the terrain and its efficiency within a particular operating regime [18]. A great deal of research and speculation has been invested in showing that an animal transitions between gaits as a means of optimizing (minimizing) the energy that is expended [18].

Some of the researches have been done in optimal selection of gaits for legged robot including Zheng, et al. achieved control of static biped locomotion on an unknown sloping surface using position sensors on the joints and force sensors underneath the heel and tow [19], Yamaguchi, et al. developed a special foot mechanism with shock absorbing material and sensor system for ground unevenness [20], Kajita, et al. have adopted an ultrasonic range sensor for measuring the ground profile and successfully implemented them on ground constituted by planes and vertical steps, such as stairs or platforms [21]. A sensor head was mounted on the tip of a pipe extending forward from the robot body to obtain information on the ground profile, with the aid of mathematical model, a foothold selection algorithm were used to calculate the footholds one and two steps ahead from the current foothold and the landing area considering safe walking condition.

Approach and Methods

Robot Design

The robot block diagram is shown in figure 1. Robot main moving gait will be using tripod method but the leg moving mechanisms were changed so that it can move more rapidly. One DC motor with output shaft rotating around 300 rpm was used for each leg. The legs are decoupled with bent high carbon aluminum so that a flexible movement can be achieved in a rotational way with the axis of rotation fixed relative to the body. The curve bent aluminums also provide impact absorption to increase the robustness of the robot. Microcontroller (PIC16F877) was used to control all the movements of the robot.

Magnetic sensors are used for leg position feedback. Three infrared proximity sensors where two located at the front of the robot and one at the rear are used for obstacle sensing. Another two limit switches are placed at the front of the robot for object sensing. Readings from sensors and data from visual processing microcontroller are fed into this microcontroller to decide the movements that will be performed. Two relays are used to control or drive each motor to achieve clockwise, counterclockwise and stop movement in order to perform different gaiting. A 11.1v, 2.2Ah lithium polymer rechargeable battery was incorporated as the power supply for controller and motors so that the robot can move freely around.

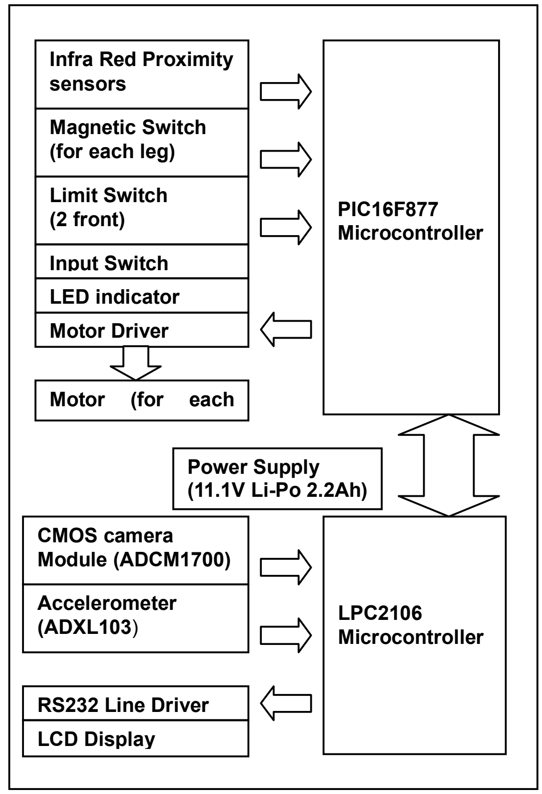

Figure 1 – Robot Block Diagram

Automatic Gait Selection Design

The method proposed for terrain recognition is described in figure 2 which show the data processing algorithm. Two main features used for recognition are the average of image color and image textures. For example, a grass field will be green in color and types of grass can be further classified by its textures in image. The method chosen must be able to cope with the available microcontroller processing power and resources.

A CIF CMOS camera (ADCM 1700) from Agilent with maximum resolution 352x288 pixel will be used for visual input. Color picture with resolution 88x72 pixel RGB output format captured from CMOS camera will be fed to a 5x5 unweighted smoothing filter to remove noise from the picture. Then the picture will be averaged to find the average color for the picture. There are many possible representations for color space, the HSI (Hue, Saturation and Intensity) space was chosen as the hue and saturation value are less affected by the brightness of the picture being captured. The color image represented in these three planes can be calculated as follows:

$$I = (r + g + b)/3$$
$$S = (\max(r, g, b) - \min(r, g, b)) / \max(r, g, b)$$

Hue (which is an angle between 0 and 360) is best described procedurally:
If (r=g=b) Hue is undefined
If (r>b) and (g>b) Hue = 120*(g-b)/ ((r-b) + (g-b))
If (g>r) and (b>r) Hue = 120 + 120*(b-r)/ ((g-r) + (b-r))
If (r>g) and (b>g) Hue = 240 + 120*(r-g)/ ((r-g) + (b-g))

Hue and saturation will be calculated from the averaged color picture and will be used as input for terrain classification.

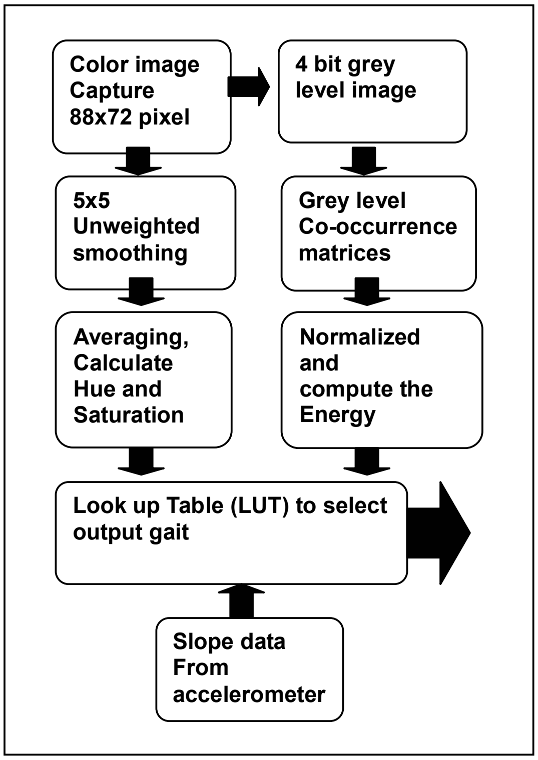

Figure 2 – Processing algorithm

Grey level co-occurrence matrices (GLCM) will be used for extraction of textural features for classification. This method was proposed by Haralick, 1973 for satellite images classification. It can be defined as a two-dimensional histogram of gray levels (2nd order grey level statistic) for a pair of pixels separated by a distance in a given direction or a tabulation of how often different combinations of pixel brightness values (grey levels) occur in the image. Texture recognition is chosen here as the image of grass field, sand poll, small stone and other terrains can be view as texture pattern in wide angle view. The same picture will be converted to a 4 bit grey level image for texture recognition purpose. Two 16 x 16 co-occurrence matrices will be calculated from the grey level co-occurrences matrices. The matrices will be normalized and the angular second moment or energy features will be calculated using the following equations. Normalization is required to transform the GLCM matrix into a close approximation of a probability table.

Matrix normalization

$$P(i,j) = \frac{V(i,j)}{\sum_{i,j=0}^{N-1} V(i,j)} \quad (1)$$

Angular second moment

$$f = \sum_{i}\sum_{i}\left(P(i,j)\right)^2 \quad (2)$$

i is the row number and j is the column number
N is the total number
P (i, j) is the normalized matrix
V (i, j) is the CLCM matrix

A single axis accelerometer (ADXL103) from Analog Device will be used for terrain slope input. Data from picture captured, hue and saturation, energy level feature calculated from GLCM and slope will be the input for a predetermine lookup table to select the most suitable gate for the robot. All the above data processing is done in a high performance microcontroller LPC2106 operate at 60MHz with 64kB on chip memory.

Result and Discussion

The robot is tested for its speed and ability in the real environment. Quad dual gaiting provides a good and stable locomotion while giving a faster speed in most of the terrain especially in highly uneven terrain. Hopping is faster but does not perform well in uneven terrain. Going down a small staircase can be achieved by using pair sequence gaiting. The figures below are taken while the robot is performing navigation in different terrain.

Figure 3 - Navigation in grass field

Figure 4 - Navigation in rough terrain

Six identified sample terrains have been created to test the terrain recognition capability of the robot. Each sample terrain measured two metre square are placed side by side. In the series of testing, the robot has to go through each test terrain for up to twenty times. If the robot successfully recognizes the test terrain, it will switch to the predetermined gaiting style designated for that terrain. The result is shown in table 1.

Table 1 - Results of Experiment.

Terrain	**Reliability (%)**
Pavement	79.7
Lawn	89.7
Grass	90.1
Sand	82.2
Stone	93.4
Rock	86.2

Previous image processing task has been carried out by PIC18F452 microcontroller operates at 40 MHz with additional external memory for temporary image and matrices storage. After the upgrade on the image processing microcontroller from the PIC18F452 to LPC2106, which is capable of data processing at 60MIPS and rich peripheral resources with 64kB on chip memory, the overall system reliability and accuracy on terrain recognition has been improved.

Conclusion

Papers Limbs or insect's leg can move both quickly and forcefully, but actuators cannot operate both at high speeds and at high torque levels. Thus, for robots, storing periodically in a spring potential some portion of their kinetic energy seems like an effective solution to the inevitably constraining actuator torque and power limits. Combination of flexible segmented body joint and embedded vision system for gaiting selection, enabled the robot to perform navigation with outstanding mobility in unstructured environments in high speed with obstacle avoidance behavior.

Acknowledgments

Preliminary works that have been done was supported by Ministry of Science, Technology and Environments under Intensification of Research in Priority Areas (IRPA).
IRPA EAR Funding
"Development of a Biologically Inspired Mobile Robot with Intelligent Behaviors"
(09-02-06-0026-EA0026)
Postgraduate study of the first author was supported by Ministry of Science, Technology and Environments under National Science Fellowship (NSF).

.

References

[1] Matthias O. Franz and Hanspeter A. Mallot. Biomimetic robot navigation. Robotics and Autonomous Systems, special issue: Biomimetic Robot Navigation, pp 133-153, 2000.

[2] Saranli, U., Buehler, M. and Koditschek, D. E., "Design, Modeling and Preliminary Control of a Compliant Hexapod Robot," in IEEE Int. Conf. on Robotics and Automation, San Fransisco, CA, April 2000.

[3] Saranli, U., Buehler, M. and Koditschek, D. E., "RHex: A Simple and Highly Mobile Hexapod Robot", in The International Journal of Robotics Research, pp 616 - 631, July 2001

[4] Buehler, M., Saranli, U., Papadopoulos, D. and Koditschek, D. E., "Dynamic Locomotion with four and six-legged robots," Int. Symp. Adaptive Motion of Animals and Machines, Montreal, Canada, Aug 2000.

[5] Altendorfer, R., Moore, N., Komsuoglu, H., Buehler, M., Brown Jr., H.B., McMordie, D., Saranli, U., Full, R.J., Koditschek, D.E. "RHex: A Biologically Inspired Hexapod Runner," Autonomous Robots 11 (2001) 207.

[6] Clark, J. E., Cham, J. G., Bailey, S. A., Froehlich, E. M., Nahata, P. K., Full, R. J. and Cutkosky, M. R., "Biomimetic Design and Fabrication of a Hexapedal Running Robot", Intl. Conf. Robotics and Automation (ICRA2001), Seoul, Korea, May 21 - 26 2001.

[7] Bailey, S. A., Cham, J. G., Cutkosky, M. R., Full, R. J., "Comparing the Locomotion Dynamics of a Cockroach and a Shape Deposition Manufactured Biomimetic Hexapod", International Symposium on Experimental Robotics (ISER2000), Honolulu, HI, December 10 - 13, 2000.

[8] Cham, J. G., Bailey, S. A., Cutkosky, M. R., "Robust Dynamic Locomotion through Feedforward-Preflex Interaction", ASME IMECE Proceedings, Orlando, Florida, November 5 - 10, 2000.

[9] Rowe, A., Rosenberg, C., Nourbakhsh, I. "A Low Cost Embedded Color Vision System.", IROS 2002 conference.

[10] Rowe, A., Rosenberg, C., Nourbakhsh, I."A Simple Low Cost Color Vision System.", CVPR 2001 conference.

[11] Barnhart, C., The MIT Cheap Vision Machine, http://www.ai.mit.edu/people/ceb/cvm.html

[12] Konolige, K., The SRI Small Vision System, http://www.ai.sri.com/~konolige/svs/

[13] Rowe, A., Rosenberg, C., Nourbakhsh, I. CMUcam Website, http://www.cs.cmu.edu/~cmucam/

[14] Omnivision Technologies Incorporated, "OV6620 Single-Chip CMOS CIF Color Digital Camera Technical Documentation," http://www.ovt.com/

[15] Ubicom Incorporated, "SX28AC Configurable Communication Controllers Technical Documentation", http://www.ubicom.com/sx/

[16] Rowe, A., Rosenberg, C., Nourbakhsh, I. "A Simple Low Cost Color Vision System," Technical Sketch Session of CVPR 2001, 2001.

[17] Yoneda, K., Hirose, S., "Dynamic and static fusion gait of a quadruped walking vehicle on a winding path", IEEE Int. Conf. on Robotics and Automation Proceedings, vol.1, pp143 - 148,12-14 May 1992

[18] Ostrowski, J., Desai, J.P., Kumar, V., "Optimal gait selection for nonholonomic locomotion systems", IEEE Int. Conf. on Robotics and Automation Proceedings, vol 1, pp 786 - 791, 20-25 April 1997

[19] Zheng, Y.F and Shen, J., "Gait Synthesis for the SD-2 Biped Robot to Climb Sloping Surface," IEEE Trans. On Robotics and Automation, vol.6, no.1, pp 86 - 96, 1990

[20] Yamaguchi, J, Takanishi, A., and Kato, I., "Experimental Development of a foot mechanism with shock absorbing material for acquisition of landing surface position information and stabilization of dynamic biped walking," IEEE International Conference on R&A Proceedings, pp 2892 - 2899, 1995

[21] Kajita, S. and Tani, K., "Adaptive gait control of a biped robot based on realtime sensing of the ground profile," IEEE Int. Conf. on Robotics and Automation Proceedings, vol. 1, pp 570 - 577, 22-28 April 1996