Ph.D., D.Sc. Teresa Zielinska, Ph.D. Terrence Goh**,*
*Ph.D. Gerald Seet**, M.Sc. Choong Kwong Chong***
**Warsaw Univ. of Technology, MEiL ul. Nowowiejska 24, 00-665 Warsaw, Poland*
***Robotics Research Centre, Nanyang Technological University, Singapore 639798*

SYNTHESIS OF MOTION OF AUTONOMOUS HEXAPOD

Abstract: Description of hexapod gaits is given. Choice of gait is one of the important steps in walking machine design. Gait type has influence to the energy consumption and walking machine adaptability to the terrain conditions. Proposed solutions are currently partially implemented in the LAVA prototype of hexapod.

1. Introduction

Walking machine operating in rich, dynamic environments must be able to effectively utilize and coordinate their limited physical and computational resources. Control of machine in natural environment requires making decisions of which and when leg to lift, and also when and where to place the leg [5, 6] so that the machine may continue to move stable along its prescribed path or machine is able to reach a prescribed goal.

Terrain following statically stable walking machine must have the possibility of walk using free gait. In free gait each leg can be lifted and placed independently based on the current distribution of available footholds.

The first formalization and solution of terrain-adaptive aperiodic gait (free gait) was given more than twenty years ago [1] for six legged walking machine. The main assumptions of this solution have been later used by many others. Free gait planning method uses terrain map information to select footholds. Static stability criterion and maximization of the minimum kinematics margin over all legs through the lifting and placing sequences are there the main points. Six legged walking machine LAVA dedicated to the environment exploration is under development in Robotics Research Centre, Nanyang Technological University, Singapore [2, 7]. In the LAVA design acceptable terrain adaptability will be meet using simple methods.

2. Analysis of walking machine mobility

3. Static stability conditions

Assume that x_1, y_1 and x_2, y_2 are leg-end coordinates considering the top planar view of the machine (Fig.1). Legs indexed "1" and "2" are interpreted as every pair of legs located on the opposite sides of the body (left, right). The XY coordinate frame is placed on the geometrical center of machines' body, and x_g, y_g are coordinates of machines' center of gravity.

Line connecting the "1" and "2" leg is expressed by:

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1}(x - x_1) \quad (1)$$

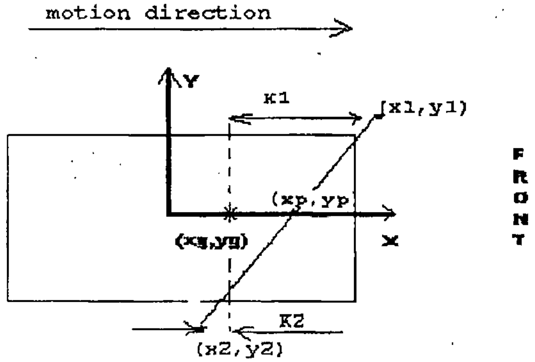

Fig. 1. Top view of the body and coordinate frame

Point of intersection of line passing x_g, y_g and oriented along the X direction (motion direction), and line connecting the legs has coordinates (x_p, $y_p = y_g$), where:

$$x_p = \frac{y_g - y_1}{y_2 - y_1}(x_2 - x_1) + x_1 \tag{2}$$

To fulfil static stability condition must be:

$$x_p - x_g > 0 \tag{3}$$

Using rel.(2) in rel.(3):

$$\frac{y_g - y_1}{y_2 - y_1}(x_2 - x_1) + x_1 > x_p \tag{4}$$

For symmetrically designed walking machine $y_1 = -y_2$. Most critical situation for the stability demand (smallest static stability margin) is when the "1" and "2" legs are on their rear limits (limits are measured along the X axis and are expressed relative to x_g). We assume that in this critical position x coordinates of the leg-ends are equal to:

$$x_{1min} = x_g + K_1 \tag{5}$$

$$x_{2min} = x_g + K_2 \tag{6}$$

where K_I can be positive or negative. Using rel.(5,6) and $y_1 = -y_2$ in (4) we have simplified static stability condition:

$$K_1 > -K_2 \tag{7}$$

The above static stability condition is always easy to meet by proper assumption of the leg-end rear limits (in Fig.1 K_1 is positive, K_2 is negative).

3.1. Possibility to move over the slope terrain

Motion planning of a statically stable vehicle includes following tasks:

- body motion planning,
- gait control,

- leg motion planning,
- joint motion planning (joint motion control).

In the design of real control machine proper distribution of control tasks must be done taking into account the hardware structure.

Analysis of LAVA mobility was done taking into account only static stable motion without dynamic properties which is proper approach for slow motion and for machine with relatively light legs and powerful motors. When the motor power is adequately greater than the power consumed during the leg motion - all the dynamics effect can be neglected.

For the forward static (symmetrically backward) movement over slope the following relationship must be fulfiled :

$$2D + 2M_s < 2x_c' \mp 2L \tag{8}$$

Where:

D - maximal possible forward, backward leg-end shift relatively to hip (in support phase),

M_s - needed minimal longitudinal static stability margin,

x_c - coordinate of machine center of gravity along axis having its origin located on front boundary of the body and oriented to the front, which means that negative direction of axis is directed to the rear of the body,

$x_c' = x_c'' - H\, tg\beta$ - coordinate of vertical projection of the center of gravity to the terrain surface.

H - height of the body, distance between machine center of gravity and its projection (projection done perpendicularly to the terrain surface),

L - length of the body,

β - slope of the terrain

It is easy to find that the machine can move by static stable gait when the slope angle β is such that:

$$tg\beta < \frac{L - 2D - 2M_s}{2H} \tag{9}$$

For machine with: $H = 9cm$, $L = 35cm$, $D = 9cm$, which also means means possibility to have of 18cm step length, $\beta < 39^0$

Other machines with following parameters:

- $H = 10cm$, $L = 50cm$, $D = 10cm$, which also means possibility to have of 20cm step length,
- $H = 9m$, $L = 45cm$, $D = 9cm$ (18cm step length),
- $H = 12cm$, $L = 60cm$, $D = 12cm$ (24cm step length),

have the possibility to go on the slope $\beta < 54^0$.

As was shown slope angle results only from analysis of static stable motion and not includes slipping conditions and the motor torque's limitations.

Considering only geometrical proportions of static stable gait six-legged walking machines having insect proportions can move on 40^0 inclined terrain.

4. Hexapod gaits

4.1. Choice of gait type

According to the periodicity of motion gaits are categorized into periodic and a-periodic. Periodic gaits according to the state of environment are the level-walking gaits (for flat terrain) and a-periodic are obstacle-crossing. The wave gaits are most stable (statically stable) and therefore they were proposed by most researchers as primary gaits. The wave gaits with greaters duty factors are proposed as the gaits over the small slopes. By proper correction of relative body leg-ends position is easy to correct the static stability margin. Such a correction should be done automatically by the on-board controller taking into account the readings from inclinometers. Thie five-legs support gait should be used on the beginning of movement when is the need of restriction of the peak power requirement, or for the movement over soft or slipping terrain. In each moment of time machine is supported by five legs which minimize the slipping possibilities and legs sinkage. The fastest wave gait is the tripod gait where in each moment of time machine is supported by three legs only. This gait does not optimize the energy consumption and is not preferred for the soft terrain. This gait should be used for the fast movement on hard and flat terrain. In the wave gaits the leg-end can only be adjusted to a small degree to avoid small forbidden areas along the pathway. If a large number of areas along the pathway are forbidden. the follow the leader gait mode (FTL) is foreseen. In FTL gait the leg simply places its foot on or close to the footprints which was previously occupied by the leg ahead of it. The forelegs form both sides of the body marks the footprints. In FTL gaits the demands of the foothold selections are reduced to minimum, but FTL gaits provide greater allowance for foot adjustment and can avoid only a forbidden areas of smaller size. An FTL gait can be periodic and a-periodic. For free a-periodic FTL gait a special algorithm of planning of leg-ends transfer , taking into account the environment conditions and type of external machine sensors must be developed. In the minimum version of the LAVA software only periodic FTL gait will be included.

4.2. Gaits time scheme

Gait period is the time in which we observe full sequence of leg-end transfer. For tripod gait T_{3v} has the smallest value, for the gait in which only one leg is transferred (slowest gait) T_{5v} is greatest. In tripod gait the time between the excitation (start to transfer) of the some leg is equal to $t_{3e} = \frac{T_{3v}}{2}$, for the slowest gait this time is equal to $t_{5e} = \frac{5\,T_{5v}}{6}$. Step length of each leg for every gait is the same and equal to s. Assuming that in this both gaits time of leg-end transfer is the some (and equal to t_t) which simplifies the control algorithms we can compare the speeds. In tripod gait the time of support phase is equal to the time of transfer phase, in slowest gait this time is five times longer than that of transfer phase. Tripod gait speed is equal to:

$$v_{max} = \frac{s}{t_t} \tag{10}$$

and speed of slowest gait:

$$v_{min} = \frac{s}{5\,t_t} \tag{11}$$

To known that the speed can change in the range v_{max}, v_{min} is easy to express the relationship between the speed and time t_e between leg excitations.

$$v = k\,v_{min} \qquad k\,\epsilon < 1,5 > \tag{12}$$

and:

$$t_e = \frac{s}{v} = \frac{s}{k\, v_{min}} \qquad (13)$$

where s is the step length (length of support leg-end displacement along the motion direction).

4.3. Beginning of movement, simplest gait scheme

To start the gait from the position when all leg-ends are on the ground, we must known when to excite every leg to produce the proper gait pattern. In the simplest case of only tripod gait and mentioned above slowest gait there are only 2 schemes of first excitation. In the tripod gait first must be excited legs no. 1, 3, 5 (or symmetrically 2, 4, 6) which means excitation of hind and front leg on one side of the body and middle leg on the other side. Next will be excited legs 2, 4 , 6 (or symmetrically 1, 3, 5). For slowest gait excitations are in constant sequence: 1, 2, 3, 4, 5, 6 (leg 1 - right hind leg, 2 - right middle leg, 3 - right front leg, 4 - left hind, 5 - left middle, 6 - left front). The next leg is not lifted until the previous one is lowered on the ground.

5. Control system

The hardware structure of control system - includes: PC host (leg CPU), motion control cards (PID controllers) connected to the amplifiers powering the leg motors. To provide position feedback, the 16 lines digital encoders are used. Leg-end 3-components KISTLER force sensor by the A/D converter delivers the data to the PC host. Control program is written in C language and is implemented in the PC host. Control cards uses National Semiconductor LM680 dedicated motion-control processors. Controllers as the bus peripherials must be programmed by host computer. Sampling rate (time of one feed-back loop run together with encored reading) slightly depends on the motor control method (PWM or voltage control) and in our case of voltage control is in the range of 400μs. The time of one micro-step on the leg level can be chosen depends on the motion properties. It was find by the experiments that this time can be not shorter than 0,03s for the smooth leg-end movement in both short transfer phase and about two/three times longer support phase. Controllers uses trapezoidal velocity profile of motors motion (so called position mode) and adequate procedures are responsible for calculation of maximum velocity and acceleration for each micro-step. On trajectory following movement, to prevent the leg-end vibrations. acceleration must be constant. Proper values of acceleration were find experimentally - for each motor separately. Those values are different for leg-end transfer and for support phase.

6. Conclusions, further works

The goal of the presented works is to develop small autonomous devices. Stability conditions and possibility to move over inclined terrain were discussed. Main rules of wave gait generation were described. Futher research will focus on development of full version of LAVA vehicle including mechanical system, software and hardware. Actuall tests are carried out on two legs test rig.

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