Stiffness Distribution Control
– Locomotion of Closed Link Robot with Mechanical Softness –

MATSUDA Takeshi
Interdisciplinary Graduate School of Science and Engineering
Tokyo Institute of Technology
Yokohama, JAPAN 226–0026
Email: matsuda@mrt.dis.titech.ac.jp

MURATA Satoshi
Interdisciplinary Graduate School of Science and Engineering
Tokyo Institute of Technology
Yokohama, JAPAN 226–0026
Email: murata@dis.titech.ac.jp

Abstract—This paper proposes a new method of locomotion control, named “Stiffness Distribution Control (SDC)”, to realize various locomotion of a closed link robot with mechanical softness. SDC directly defines the reference stiffness coefficient at each hinge by SDC string which represents the distribution of the stiffness. This simple method does not need costly calculation at all and thus is suitable for controlling closed link robots. We build “BIYOn” as the prototype of closed link robots, the variable stiffness hinge (VSH) of which is newly designed. SDC is experimented on BIYOn and then it's found that SDC is effective in a controlling locomotion in practice. We also develop a systematic optimization method of stiffness distribution composed of two-stage approach and succeed in optimization to obtain a fast and smooth rolling motion and a sudden stopping motion.

I. INTRODUCTION

Applications of robotic system is rapidly expanding to various non-industrial fields such as nursing, entertainment, education, and security where robots have to do their task among other people and other robots in the same environment. The robots which are designed to coexist with humans are required to be absolutely safe; they must not harm people in any possible situations. Conventional approaches to realize such safety are usually based on software servo technique; namely, compliance at the joint is emulated by gain control. However, this method cannot react to impulsive disturbances because of control delays. It also cannot cope with faulty operations or breakdown of controller processors.

An alternative approach to secure the absolute safety that does not rely on the control is to embed passive softness in the robot hardware. We consider that there are two important requirements to realize such safety, a) mechanical softness of the robot hardware, b) closed link configuration of the robot. The former guarantees compliance against any collisions or impacts. The latter is advantageous for safety, because of the round surface without any protrusions.

We have proposed a modular robot called “BIYOn” based on the above idea [1]. It is a crawler robot made of identical segments. Instead of driving relative angles between the adjacent segments, each segment has a motor that controls the torsion stiffness between the segments. This design is to satisfy the requirement a), and the loop configuration satisfies b).

Control of closed link system usually requires heavy calculation of kinematics/dynamics [4], though there are some exceptions1. Even if its dynamics is obtained explicitly2, various frictions and boundary constraints caused by the ground contact is very difficult to be taken into account. Moreover, BIYOn is regarded as the hybrid system [2], [3], which is a combination of differential equations (dynamics) and discrete logic (ground contact conditions), requires even more computational cost (Figure 2).

In terms of intrinsic safety, servo control based on kinematics/dynamics does not make sense, because the robot merely follows a given target trajectory, namely, a robot is deprived of quick reflection to unpredictable disturbances. The compliance control is advantageous to reduce the calculation cost. Instead of costly calculation of kinematics/dynamics, it implicitly determines the geometrical shape of the link system owing to its loop configuration.

In order to cope with the difficulties in closed loop robot control, various attempts have been made. One of such ap-

1Kinematics of a closed few-link mechanism, containing less than six links, is easy to solve.

2There are several methods to obtain a systematic computational scheme of the dynamics of closed link mechanism [5], [6], [7]. In the methods, the closed loop is replaced by open loop system by cutting at some hinge, and restored by adjusting boundary conditions at the cut point. These methods are applicable only when there are no singular points in the configuration space.
proaches is to reduce the complexity of kinematics/dynamics. Omata et al. [9] proposed a locomotion control for their five-link crawler robot. They made three hinges unactuated and specified a rolling motion around one axis on the floor. This is a very straightforward way to remove redundancies and simplify the kinematics/dynamics, however generalities of the method are almost lost. Another approach is to use evolutionary computation. Matsuo et al. [10], [11] applied the Genetic Algorithm (GA) to their six-link crawler, all the hinges of which are directly actuated by motors. They optimized their control algorithm by exhaustive calculation of dynamics simulations. GA gives an optimal solution for a specific robot, however it does not suggest any general design methodology. Yokoi et al. [12], [13] proposed a method called “Direct Compliance Control” for grasping motion of a redundant parallel link manipulator. It realizes force control at the end effector by introducing compliance at each joint. This method only considers external forces at the end effector, thus cannot be applied to crawlers that have multiple contacts with the ground.

Our purpose is to develop a systematic design method of closed link robot control, which has low computational cost and easy implementation.

In this paper, we propose a new control method to generate locomotion of closed link robots on the ground called Stiffness Distribution Control (SDC). The principle of the method is as follows: Assuming that stiffness at each hinge of the closed link can be controlled, the overall shape of the loop depends on the distribution of hinge stiffness. Namely, we can control the shape of the loop by giving appropriate stiffness distribution on the loop. If the distribution is continuously changed, dynamic motion of the loop such as locomotion (rotation) will be realized. For the simplicity, we use a unique fixed stiffness distribution. The stiffness coefficient at each hinge is determined by this stiffness distribution and relative position of the hinge in the loop defined by the ground contact condition. At every moment when the contact condition is changed by the movement, a new stiffness coefficient is reassigned to each hinge by using the same stiffness distribution. This method requires only a simple shifting operation of the stiffness coefficients determined by the binary input (Contact or Non-contact) at each link.

II. HARDWARE OF MODULAR CRAWLER

In this section, we give a brief description of the hardware system of BIYOn (Figure 1). BIYOn is a crawler type robot

3 A closed five-link mechanism is 2 DOF by Gr"ubler’s formula [8].

Table I: Major Specifications of BIYOn

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num. of Connected Modules</td>
<td>8...10</td>
</tr>
<tr>
<td>Mass (per module)</td>
<td>162(g) (w/o com. cables)</td>
</tr>
<tr>
<td>Size (per module)</td>
<td>W88 × L90 × H20(mm)</td>
</tr>
<tr>
<td>Distance bet. neighbor modules</td>
<td>74(mm)</td>
</tr>
<tr>
<td>Sensors</td>
<td>Ground (touch) switch only</td>
</tr>
<tr>
<td>Batteries</td>
<td>External supply</td>
</tr>
<tr>
<td>MCU</td>
<td>PIC16F876</td>
</tr>
</tbody>
</table>

A closed five-link mechanism is 2 DOF by Gr"ubler’s formula [8].
Fig. 5. Relative coding system for SDC. The labels of the hinges are relatively defined on the basis of ground contact. The foremost hinge touching the ground is called F+0, F+1, F+2, F+3 follow in counter-clock-wise. Likewise, R–0, R–1, R–2, R–3 are defined from the rearmost hinge on the ground. Whenever a link detaches from or attaches to the ground, this coordination is renewed. 'G' is given to hinges on the ground. When some hinges exist between R–3 and F+3, these hinges are labeled 'S'.

SDC string: LHHL__HHLL

Fig. 6. Simple stiffness distribution

where $E$ is Young’s modulus, $I$ is second moment of area, and $l$ is the length of the leaf spring.

When $a = tl (0 \leq t \leq 0.5)$, the stiffness ratio $r$ becomes as follows.

$$ r = \frac{k}{k_{\min}} = \frac{1}{16t^2(1-t)^2} \quad (3) $$

The maximum stiffness ratio $r_{\text{max}}$ is 1.7 in the VSH.

III. STIFFNESS DISTRIBUTION CONTROL

Stiffness Distribution Control (SDC) is a method to control locomotion of a closed link system. SDC controls torsion stiffness at each connection axis between the modules.

We define a relative coding system to give labels to hinges and relative angles between adjacent modules (Figure 5).

A. Stiffness Control by SDC string

SDC string represents the distribution of the stiffness. It is a string in form of “ABCD_EFGH”, where each character corresponds to a discrete level of stiffness $k_i$ at the location R–3, R–2, R–1, … F+2, F+3. We also define “standard stiffness” around which the stiffness coefficient is varied. We use $0.4$ (mN/rad) for the standard stiffness coefficient. This value is chosen to give a convex curvature on the loop. The standard stiffness is allocated to hinges with label G and S. From now on, the unit of stiffness coefficients are not written.

By using SDC string, we can calculate torque $\tau_i$ at each hinge, where $i$ denotes $i$-th hinge from R–3 to F+3.

$$ \tau_i = k_i \cdot \dot{\theta}_{i,r} + d \cdot \dot{\theta}_{i,r} \quad (4) $$

The second term of Eq. (4) represents viscous friction in the VSH. We assume that the actual stiffness coefficient of the hinge $k_i$ converges to the reference coefficient $\hat{k}_i$ with time constant $T$ shown in Eq. (5).

$$ \dot{k}_i = \frac{1}{T} (\hat{k}_i - k_i) \quad (5) $$

B. Simulation & experiments

We have evaluated the SDC by dynamics simulation. We adopt “Open Dynamics Engine ver0.5” to simulate the robot locomotion throughout this paper. The real specifications of BIYOn is used for simulation. Other parameters are, $T = 0.6$ (s), $d = 0.005$ (mNs·rad$^{-1}$) and simulation step = 5.0 (ms).

The SDC string used in the simulation is LHHL__HHLL (L:0.4, H:0.6). We put two hard segments (HH) near the foremost and rearmost contact hinges, that may push the front and pull up the rear shown in Figure 6. Snapshots from the simulation are shown in Figure 7. In the simulation, obtained locomotion velocity is 0.29 (m/s) after the robot reaches a steady state.

Next, we have conducted experiment on the BIYOn hardware using the same SDC string. The snapshot of the experiment is shown in Figure 8. Obtained speed is 0.08 (m/s). The
TABLE II
CODING SYSTEM OF STIFFNESS COEFFICIENT

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.5</td>
<td>1.6</td>
<td>1.7</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>C</td>
<td>2.0</td>
<td>2.1</td>
<td>2.2</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
<td>2.6</td>
<td>2.7</td>
<td>2.8</td>
<td>2.9</td>
</tr>
<tr>
<td>D</td>
<td>3.0</td>
<td>3.1</td>
<td>3.2</td>
<td>3.3</td>
<td>3.4</td>
<td>3.5</td>
<td>3.6</td>
<td>3.7</td>
<td>3.8</td>
<td>3.9</td>
</tr>
<tr>
<td>E</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

reason why we get slower speed compared to the simulation is not clear. One of the possible reasons is that we could not realize equal characteristics among the modules. Another possible reason is a large friction in the VSH.

IV. OPTIMIZATION OF STIFFNESS DISTRIBUTION CONTROL

In this section, we consider optimization of SDC based on simulations. Although the simulation parameters are the same as Section III-B, we use SDC strings with higher resolution. The stiffness coefficient varies from 0.0 (free hinge) to 4.0 (ten times of the nominal stiffness value), discretized with 41 levels (TABLE II). For instance, C6 represents 2.6.

In order to reduce the computational cost of dynamics simulation, we adopt a two-stage optimization strategy. The first stage, which is called Hinge-Wise (HW) optimization, we get the local (coarse) optimal stiffness coefficient for each hinge by focusing on one particular hinge and allowing only two values to other hinges. The second stage is called Collective Decent (CD) optimization that is a kind steepest descent method applied to a collection of SDC strings. By this method, we are able to fine-tune the result of HW optimization to get the best solution. (It does not guarantee the global optimum in the strict sense.)

Each SDC string is tested by dynamics simulation of 20 (physical) seconds, and evaluated by its ability to generate locomotion from the stationary state. The robot is hold at the starting position during the first four seconds, then in the subsequent six seconds, it starts locomotion, but this transient phase is neglected in the evaluation. The SDC string is evaluated by the following 10 seconds by the average locomotion speed (m/s) and (vertical) vibration speed (the average of absolute vertical speed (m/s) at every sampling time (0.1 s)).

In Section IV-A, the first stage of optimization is described. Namely, by the HW optimization, we are able to reveal the qualitative functionalities of each position of the stiffness distribution. The local optimal SDC string is obtained by considering several aspects such as locomotion speed, vibration and reliability (the ability that the string always generates locomotion to a certain direction).

The detail of CD optimization aiming at improving locomotion speed is described in Section IV-B. Some simulation results of locomotion will be shown in Section IV-C. In Section IV-D, optimization result of stopping motion (SDC string which draw up the robot) will be shown. Hereafter, we call a robot controlled by some SDC string an “individual”.

A. Hinge-Wise optimization of SDC

We have some intuitive understanding of role of each hinge in the loop robot. For instance, we put high stiffness coefficient at F+0 and F+1 and they push the robot to the forward direction. Other hinges may have some specific functionality according to the desired motion. We propose HW optimization is to find qualitative functionality of each hinge. The method is as follows.

1. To reduce the computational cost, limiting hinge stiffness at two levels (A4 and A6) except for one hinge.
2. Evaluate all possible binary combinations to get qualitative functionality and optimal stiffness coefficient at the hinge.
3. Apply (1), (2) to all the hinges to get the local optimal SDC string. (This is used for the initial string to the further tuning in the CD optimization.)

Figure 10 is a scatter plot of all the individuals evaluated by locomotion speed against the stiffness. Each strip corresponds to allocated stiffness value for one hinge, and the distribution of speed for all the individuals. For example (Figure 10(b)), when stiffness 1.4 is assigned to R–2 hinge, most of individuals make forward locomotion, however some shows reverse locomotion. From these plots, we can understand qualitative role and importance of each hinge for locomotion through different performances among all stiffness coefficients.

Figure 11 shows locomotion speed and vibration of all the individuals for each hinge. We can also read some useful information from this plot. For instance, R–1 has strong positive correlation between speed and vibration at range of 0.3, but it becomes strong negative at range of 0.6. If the value is larger than 1.6, high speed is realized without large vibration. Figure 9 summarizes the tendencies we found in those plots. Observed tendencies can be classified into four modes. (There is no rigorous explanation of the reason why we have four different modes.)

1st: Intermittent rotation with low speed and large vibration.
2nd: Transient from intermittent rotation to continuous rotation. Vibration is decreased along with the speed.
3rd: Smooth rotation with low vibration. (Desired)
4th: Unstable bouncing.

The qualitative knowledge we have extracted from the results of HW optimization is summarized as follows.
Fig. 10. One dimensional scatter plots on velocity per stiffness value. Because of a symmetric robot mechanism, plots for R-i and F+i have the reversed characteristics. An area of a square at “Over” represents a number of strings which generate a rolling motion at over 0.4(m/s).

R–3: Higher stiffness gives forward direction, and low one provides 2nd mode.
R–2: Higher stiffness gives 3rd mode.
R–1: Higher stiffness gives 3rd mode, however it does not affect the direction of rolling.
R–0: Stiffness must be low for forward locomotion.
F+0: Stiffness must be higher than the standard coefficient (= 0.4) to get forward direction. However, it is too high, locomotion becomes 1st mode.
F+1: Higher stiffness often gives high speed locomotion, however sometimes it brings 4th mode. It doesn’t affect the direction.
F+2: Low stiffness gives 2nd mode and high probability of forward direction. However it must not be too low to obtain 2nd or 3rd mode.
F+3: Low stiffness gives high probability of forward direction.
Higher is better (type III).

Typ e I) Equilibrium. Do nothing.
Typ e II) Lower is better. Shift down.
Typ e III) Higher is better. Shift up.

We derived the local optimum SDC by using the knowledge in total.

Local optimum: \( A_4D_3D_3A_1\ldots A_6B_9A_3A_1 \) \hspace{1cm} (6)

B. Global optimization by collective descent method

In this subsection, we describe a method to fine-tune the local optimal solution obtained (Eq. (6)). CD optimization is an incremental optimization method based on steepest descent method. Performance of the whole individuals in a neighborhood of a certain central SDC string is evaluated first, and then the center is shifted to the steepest direction, which improves the performance by using certain criteria. We use (Eq. (6)) as the initial central SDC string.

Figure 12 shows the procedure of CD optimization. We explain the procedure along with the flow in this figure.

a) Generate individuals in a neighborhood of the central SDC string.: The set of individual in a neighborhood is defined as follows. For instance, if the central SDC string is \( A_1D_3D_3A_1\ldots A_6C_7B_9A_2 \), we allow three stiffness levels around the central value at every position. Therefore it is given by a combination such as,

\[
\begin{bmatrix}
A_2 & D_4 & D_8 & A_0 & A_4 & C_6 & A_0 & A_1 \\
A_3 & D_5 & D_9 & A_1 & A_5 & C_7 & B_9 & A_2 \\
A_4 & D_6 & E_0 & A_2 & A_6 & C_8 & B_1 & A_3
\end{bmatrix}
\]  

Each neighborhood is divided into three sets; Lower, Middle and Higher. These sets include the same number of individuals. If we focus on the hinge \( F+1 \), they are

\[\text{operations in each hinge} \]

\[\text{mean values} \]

\[\text{top} \]

\[\text{variance} \]

\[\text{Sum} \]

Higher is better (type III).

Fig. 12. One cycle of CD optimization method

**TABLE III**

**RATING OF STRING SET**

<table>
<thead>
<tr>
<th>criterion</th>
<th>best</th>
<th>middle</th>
<th>worst</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>(b)</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(c)</td>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

where “*” denotes some levels in the neighborhood (7).

b) Evaluate all the individuals by simulation.: Each set is evaluated by the following measures.

(a) Mean of locomotion speed
(b) Variance of locomotion speed
(c) Number of individuals within top 2.5%

Measure (a) is to guarantee the average high performance, (b) is to suppress the dispersion of the performance and (c) is to pursue the highest performance. From the engineering point of view, we have to combine these measures to get a realistic solution. In order to compare different sets, a total point of each set is calculated by using rules in TABLE III.

Each set has three points corresponding to the measures (a)–(c). For instance, if the set got the first place in terms of mean locomotion speed it gets 2 points. Other measures are also evaluated in the same fashion, and the total point represents evaluation of the set.

c) Shift the central SDC string.: Based on the total evaluation of each set, the central stiffness value is shifted to the next level. Depending on the pattern of total points distribution of the High, Middle, Low sets, to shift up or to shift down or unchanged is determined by the rules in Figure 13. By applying this procedure to every hinge, we obtain a new SDC string for the next iteration.

d) Repeat above until it converges.: 

C. Results of CD Optimization

In Figure 14, the transition of the central SDC string is shown. Starting from the initial SDC string (iteration=0), it converges to a small periodic oscillation between two SDC strings after the sixth generation. Therefore, we judged it is converged to the global optimum.

The result is

Global optimum: \( A_1D_8D_9A_1\ldots A_1B_9A_4A_1 \) \hspace{1cm} (8)
V. DISCUSSION & FUTURE WORK

There are several issues remained for future work. In hardware, we have to improve our module of mechanical softness in terms of reliability, controllability and low-friction design. Actually we are now working on another type of VSH.

Another issue in hardware is that the prototype BIYOn described in this paper is one-dimensional. We need additional degree of freedom to realize turning motion on a plane. In order to do this, we need to add more axes on the crawler, that require complicated control.

As software or algorithm issues, unlike Genetic Algorithm, we do not scan over the entire space SDC string, thus we cannot guarantee that the obtained string gives the global optimum. (In a sense, our result means that the evaluation landscape of our problem is relatively smooth.) Nevertheless, our method is still advantageous because it indicates functionality of each hinge which is useful to tune up the stiffness distribution. We believe this is very important in practical applications.

Some extensions of the method also can be considered. For instance, we optimize only a single SDC string for each of the rolling and stopping motion, however it is better to prepare several strings and apply them depending on phases, such as standing motion from standstill, acceleration or deceleration and steady movement, of a desired locomotion.

VI. CONCLUSION

In the present work we propose a new method of locomotion control, named “Stiffness Distribution Control (SDC)”, to realize various locomotion of a closed link robot with mechanical softness. SDC directly defines the reference stiffness coefficient at each hinge by SDC string which represents the distribution of the stiffness. This simple method does not need costly calculation at all and thus is suitable for controlling a closed link robot. We build BIYOn as the prototype of closed link robots, the variable stiffness hinge (VSH) of which is newly designed. SDC is experimented on BIYOn and generate a rolling motion in practice. We also develop a systematic optimization method of stiffness distribution based
on collective descent method and succeed in optimization to obtain a fast and smooth rolling motion and a sudden stopping motion.

SDC can apply only planar closed link robots now. Some extensions are necessary that we utilize this method in various kinds of closed link robots. Nonetheless, the newly developed control method will allow us to simplify a problem of controlling closed link robots significantly.

ACKNOWLEDGMENT
This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Exploratory Research, 16650036, 2003.

REFERENCES