Concept Development Of Biomimetic Centipede Robot StriRus

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***Abstract*—In this paper, we introduce a modification for legged locomotion and methods for biomimetic centipede robot design. Biomimetic centipede robots can be well-suited to a number of applications, including search-and-rescue around demolished rubble, logistics in rocky and hazardous areas, and more. The design space for such robots is quite large, with numerous open possibilities for body and leg shapes, configurations, and numbers of components. In contrast to similar robotic platforms proposed prototype can move in any direction. Moreover, proposed design allows robot to operate in either omni-direction or conventional states without changing components. It was shown that new design provides better cross-country passability. Structural synthesis of Biomimetic Centipede Robot StriRus was made using evolutionary algorithm and simulation, which includes optimization the number of legs and angles between neighbor legs. Crosschecked angle optimization was done using kinematics.**

I. Introduction

Biomimetic centipede robots well-suits to a number of applications, including search-and-rescue around demolished rubble, logistics in rocky and hazardous areas. In order to use their maximum capacities it is important that their design is appropriately optimized. The benefit of this type of locomotion concepts is that wheel kinematics and leg off-road capacity are combined in a single locomotion. To utilize full potential from this locomotion, structural synthesis should properly be done, which is s a part of robot design.

Robot design is a complex task, which is usually divided into numerous sub-tasks, which often remain interrelated. One of them is body design. First, a suitable body type has to be selected. In many cases, biomimetic approaches can be useful on this stage as well. For example, humanoid-like robots, snake-like robots, or fish-like robots. In our paper, we will concentrate on a centipede-inspired design, which is known to offer numerous advantages for passing through rough terrains. After body form selection, design parameters related to body characteristics like length, height, number and type of feet, need to be selected. These design parameters influence multiple aspects of the robot performance : weight, energy consumption, volume, and convex hull, as well as the ability to pass through different types of rough terrains.

When we are creating a new biomimetic robot, it is not necessary to copy a full structure of an animal. Typically animals need more DoF in their body for life being. However in robotic analogue usually we just get an inspiration of a structure only for locomotion task. Hence, we need to combine efficient mechanical and biological approaches for creating an effective robot.

The remainder of the paper is organized as follows. Following this introduction, we will provide a brief analysis of biomimetic robots. Then, we will discuss mechanical design, which consists of a hardware design part and deriving forward and inverse kinematics tasks. Next part is modeling simulation. There are several sub-parts in it, like optimization based on kinematics and dynamics. Finally, future steps are discussed, together with a forward-looking conclusion.

II. Researches with similar robots

The above presented robots have an attempt to create hybrids between wheeled robots and centipedes, in order to get the "best of both worlds". The driving method of the legs (synchronized but out-of-phase; flexible) presents another consideration, which not presented here.

A. Boston Dynamics RHex: hexapod robot

Boston Dynamics RHex [1] is a hexapod-type robot (Fig. 1). It's body looks similar to the robot model we will use further in this work. Independently controlled legs produce special gaits that propel it over rough terrain like stairs, stone ridge, etc. One of the gaits provides an opportunity to jump. The leg shape provides smooth movements. However, the robot also has several drawbacks. First of all, it is high energy consumption since it contains six motors. Also, this robot has some difficulties related to it controllability.

RHex has several modifications [2], the structure is the same, but more powerful motors, more capable batteries, better computers were installed. In particular, X-RHex became the rst robot of it's size to support a payload computer that includes a multi-core programmable GPU. This robot type was a first famous robot with this kind of locomotion. It is a versatile robot, which can be used both in open and indoor areas.

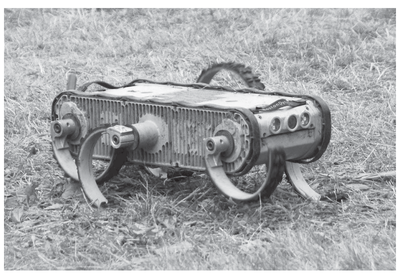


Fig. 1. Boston Dynamics robot RHex

B. Gakken Mechamo Centipede: house centipede inspired robot

Gakken Mechamo Centipede [3] is the robot (Fig. 2), which has similar kinematics scheme to the robot model designed in this work. In contrast with other robots from this comparison list, the robot has to rotate all his legs from one side simultaneously. The large number of legs may provide a good cross-country passability on a rough terrain and loss of a leg will not be critical for the robot. However, it decreases robot components durability. Moreover, a small height of leg decreases it rough terrain capabilities.

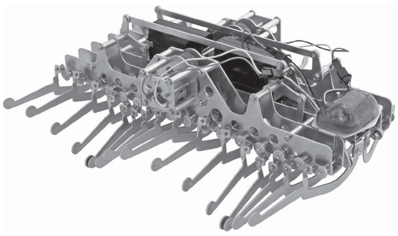
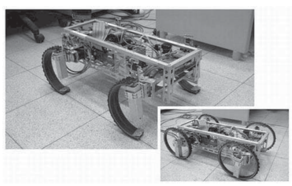


Fig. 2. Gakken Mechamo Centipede robot – house centipede inspired robot

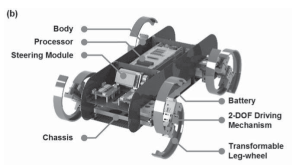
C. Quattroped and TurboQuad: leg-wheel transformable robot family

The Quattroped [4, 5] and TurboQuad are a leg–wheel transformable robots (Fig. 3). Quattroped [6] has quite big issues with mechanical part (durability and stability). It was the main reason for inventing an improvement version of this robot, which was called TurboQuad. When it (both robots) uses the legs, it's kinematic scheme is similar to the robot RHex, in the case of wheel operation mode it is similar to a vehicle. It provides high speed on a flat terrain, but the robot construction becomes very complex, which decrease robot robustness. Only four legs, in some cases, make the robot unstable.

In contrast with RHex, this robot is more suitable for outdoor tasks, because of leg–wheel. This feature provides more speed in open spaces.



(a) Quattroped robot



(b) Improved version of Quattroped robot – TurboQuad

Fig. 3. Leg-wheel transformable robot family

D. Whegs II: bending robot

Whegs II [7, 8] (Fig. 4a) uses a strategy of locomotion that combines the simplicity of the wheel with the obstacle-clearing advantages of the foot. Despite the difference in leg height compared to the RHex robot, in some cases, Whegs II can provide the same motion capabilities. It became possible by using the segmented body. On another side, this feature makes the robot more difficult to manufacture and to control. This robot has several modifications. The main differences are their size, amount of legs and some mechanical solutions. The shape of a leg is near the same (Fig. 4b).

This robot family is united by the leg shape. Other parts can be different. Despite of this, all of these robots can be useful both in indoor and outdoor areas and can be a good competitors.

(a) Whegs II bending robot

(b) Whegs with 4 legs and without segments

Fig. 4. Whegs robot family

Comparison analysis between the above-presented robots is given in Table I.

TABLE I. Comparison of hexapod-type robots

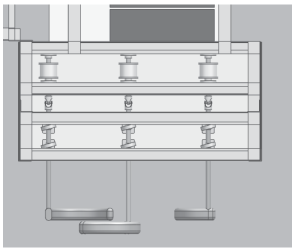
Parameters	RHex	Gakken Mechamo Centipede	Quat-troped	Whegs II
Length, mm	540	320	600	470
Width, mm	200	140	190	360
Height, mm	127	100	140	50
Mass, kg	8.2	1.1	8.6	3.86
Legs number	6	32	4	18
Leg weight, mm	175	50	175	100
Leg mass, kg	0.1	0.02	0.38	0.05
Speed, m/s	1.6	0.1	2	1.5

All these robots, excluding Gakken Centipede, were created for scouting task. It means that their parameters like magnitude, clearance and etc should be in some boundaries. These boundaries help to understand how to create a robot, which can work in the same areas. The boundaries values can be easily explained. Such width needs to be less than a door size. Usually, a door width is about 700 mm. Even better if a robot width is lesser than 2/3 of a door size and all prototypes fulfill this condition. In indoor navigation length also has some restrictions, otherwise, it cannot move in corridors and tight rooms. Robots should be shorter than 1 meter. Mass depends on other parameters. High speed is unnecessary in indoor and hazardous areas, but quite useful in open areas. All these boundaries are also convenient for our prototype.

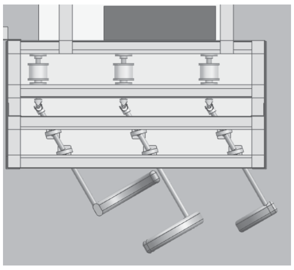
III. Mechanical design

A. Robot design

The main goal of this project is to create a modification for legged locomotion, but its a complicated task. So, the first step is to create a prototype, which can prove this concept. As



(a) Conventional state



(b) Omni-direction state

Fig. 6. Two possible legs states for StriRus robot. We can change both states without changing components

an analogues, scouting (indoor and outdoor) task was chosen as the first task. It restricts us in robot magnitude, hence in hardware and software parts too.

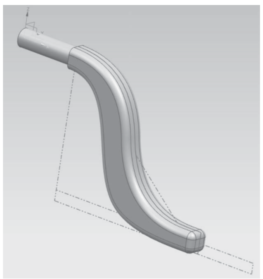
According to the comparison analysis, which was presented, we understood boundary parameters. In order to create the best centipede robot, structure synthesis task was assigned. Deeper explanations of structure synthesis task are given in Motion simulation part.

B. Principal blocks

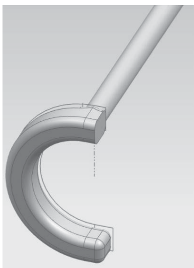
The prototype has several novelties, which are presented in this section.

1) Legs: Leg shape is a very important part of this type of robots. Leg shape changing can entail both improvements and drawbacks in cross-country ability and functionality. For instance, some shapes provide the swim possibilities, but others – dont.

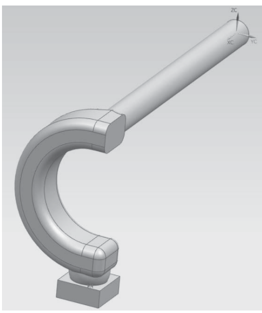
Firstly, our own designed leg shape was invented (Fig. 5a), but after some simulation experiments legs from RHex were taken [9] (Fig. 5b).



(a) First leg shape



(b) RHex leg shape



(c) Our own modification of RHex leg

Fig. 5. Several possible CAD models of StriRus leg

Moreover, we find how to improve RHex shape. We will add a passive foot at the end of leg and contact with the ground would become longer. It would increase platform terrain crossing capacity. (Fig. 5c).

2) Omni-direction state: Possibility to move in all directions without changing orientation is the real novelty of this project. We named it omni-direction state. Moreover, our prototype can be either in "conventional" state (Fig. 6a) or in "omni-direction" state (Fig. 6b), without changing hardware. It can be done via the special mechanism, which will be patented. Omni-direction state was inspired by Swedish wheel.

The main principle is the following. For moving in all directions without changing orientation, our device should have the summary force which oriented to desired direction (Fig. 7). We can obtain it using universal joint and movable walls. This device is also compromised because the cost of omni-direction state is velocity in each direction. And it can be parametrized via angle between body and legs.

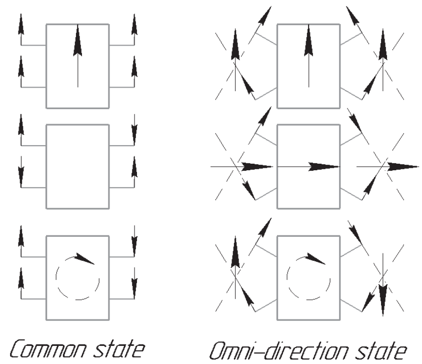


Fig. 7. Vector representation of forces in the conventional and omni-direction states

It can be implemented using this concept scheme (Fig. 8). This scheme will be patented soon.

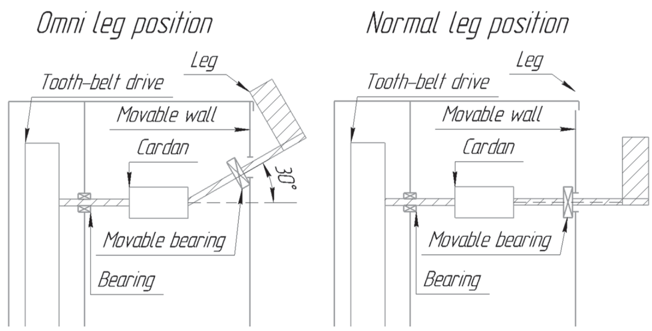


Fig. 8. Hardware implementation of both omni-direction and Convectional concepts in one device

As movable bearing ball bearing is used. Also, it has two 2 movable walls instead of 1. We have to add one, because we want to allow rotation only in one direction, otherwise 2 DoF for each leg is allowed. How does the real one works can be understood in (Fig. 7).

3) Modular system: Pursuant to the design of this prototype, the robot can have several modules. It provides better cross-country ability and the possibility to bend between segments (Fig. 9).

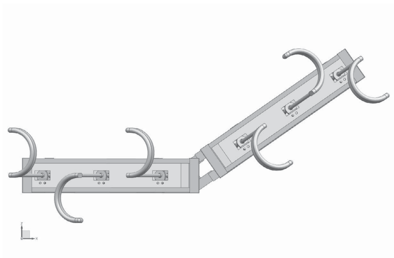
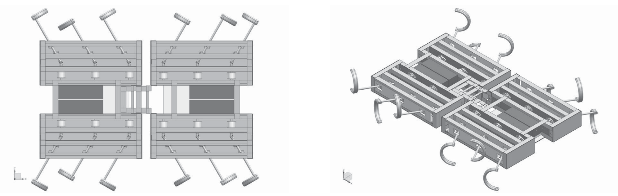


Fig. 9. Segmented StriRus can bend between segments

4) CAD prototype: Finally, the robot parameters are following:

- geometry – $790 \times 650 \times 76$ mm;
- body mass – 1.9 kg, overall mass – 17 kg;
- angle between legs can be any;
- max angle between body and leg – $30°$.

It can be tighter, but we try to make it as cheap as possible and without bespeaking anything. There are top view and isometric view of the prototype (Fig. 10)



(a) Top view (b) Isometric view

Fig. 10. StriRus CAD model with all mechanical components on-board

C. Kinematics

Kinematics is a branch of classical mechanics that describes the motion of points, bodies (objects), and systems of bodies (groups of objects) without considering the mass of each or the forces that caused the motion. In most robots, this knowledge is necessary, because control can be based on it.

For this type of robot deriving forward kinematics (FK) and inverse kinematics (IK) is a challenging task. The main reason is that it has a lot of legs. In our case the legs position is changed each time, it is the main challenge in this part.

Several papers were read [10–12] and after deep study of the problem, another approach was used.

1) Forward Kinematics: When we are talking about kinematics we assume that our frame is positioned on the ground. So, lets also assume that we have a flat ground, otherwise it would be a much more complicated task.

According to robot design, in each module and side, legs move simultaneously with a constant offset between legs. For instance, one side of the module consists of 3 legs. The angle between neighbor legs is equal $120°$. Hence, if a first leg has 0-degree angle between body frame and leg, other two have 120 and 240 degrees respectively.

In FK ambiguities in choosing what legs connected with the ground can be found. To overcoming it, some restrictions were assumed. Unfortunately, the analytic solution cannot be derived here.

Algorithm 1: Forward kinematics. High level algorithm

Input: Ang – angle for each motor
Output: X – position and orientation
Constants: Platform geometry (links length)
begin
  Find coordinates of legs, in regard to body;
  Erase unsatisfactory coordinates (higher than body coordinate);
  if *in module side there are no points* **then**
    choose body edge as the point;
  end
  Find all possible planes without point repetitions;
  Choosing a plane and find all points belonged to the plane;
  Find body orientation, $X(4:6)$;
  Find body position $X(1:3)$;
end

2) Inverse Kinematics: There is only numerical solution can be used. The main idea is to find an intersection between leg workspace (in our case it is a circle) and a line, which belongs to the flat terrain.

Some ambiguities can be found here too. For instance, in some cases we cannot determine which leg touch the ground, In this case, we assume that the lowest number is acceptable. It means, that we have legs number 1, 2, 3 and etc. So, if legs 2 and 3 are acceptable, leg number 2 will be chosen. There is the algorithm, which explains the main steps.

Algorithm 2: Inverse kinematics. High level algorithm

Input: X – position and orientation
Output: Ang – angle for each motor
Constants: Platform geometry (links length)
begin
  Find legs coordinates, in regard to body frame;
  For each leg, find a circle (leg workspace) and line intersection;
  Apply assumptions and receive Ang;
end

IV. Modeling simulation

Optimization is one of the most important tasks in the design because it helps us to decrease product price and efficiency.

In the first subsection, angle optimization is covered. In the second — structural synthesis.

A. Optimization based on forward kinematics

This robot type has some issues, one of them is oscillations. At the result, control becomes complicated and inaccurate. Hence, in order to overcome it, we may partially solve it by changing an angle between neighbor legs.

Our objective function is next. We need to maximize Z position and minimize STD. Simultaneously, we should minimize RMS and STD angles in both directions (roll and pitch). The important moment that the moving direction is also important. The objective function is the following:

$$F = \sum_{i=1}^{4} \omega_i \cdot (\frac{1}{\omega_{z1} Z^i_{rms} - \omega_{z2} Z^i_{std}} + \\ +(\omega_{p1}\alpha^i_{rms} + \omega_{p2}\alpha^i_{std}) + \\ +(\omega_{r1}\beta^i_{rms} + \omega_{r2}\beta^i_{std})) \rightarrow min \quad (1)$$

where superscript $i = \{1, 2, 3, 4\}$ is mean a values, which received from moving 1 – forward, 2 – left, 3 – right, 4 – rotation; Z is a position in Z axis; α, β are roll, pitch orientation values; ω_i is weight coefficient for each direction, $\omega_{z,roll,pitch}$ are the weight coefficients.

In our case we can just find all possible solution inappropriate time because we need only to check 36 angles · 4 directions · 100 experiments for each direction · 144 steps in each. As a result of work, we got 120 degree angle between legs.

B. Structural synthesis and optimization based on dynamics

Full research can be read in [14]. The road-map for this section is the following. First, we will discuss the fitness function and the design parameters which will be optimized. Then, we will discuss the generation of the parametric robot and terrain models. And then, we will introduce the optimization algorithm.

1) Robot math model: The geometrical model of the robot is represented as a 3D box body with several legs on each side. Each leg has a constant offset of rotation angle relative to it's neighboring leg.

Legs do not have any joints, are not separately actuated, and rotate relative to the link point with the body. The following parameters influence the body length:

- number of legs γ;
- angle between neighbor legs x;

These parameters are related in the following way.

$$L_{body} = 2 \cdot \text{offset}_{first\_hole} + ((\gamma - 1) \cdot \\ \cdot \text{legs}_{height} \cdot sin(\omega) + q) \quad (2)$$

where q is the offset between legs. Furthermore, we define the fitness function for the robot, which will will be used in the optimization problem.

In our case, we have multi-objective optimization, from the one side, we are trying to maximize the cross-country passability of the robot (i.e. how far away it can travel on the rough terrain in the given time). From another side, we are trying to minimize the length of the body. One of the approaches to solve the task is using scalarizing. The canonical additive-multiplicative scalar function is used.

$$F = \beta \left(\omega_1 \cdot \delta + \omega_2 \cdot \frac{1}{(\gamma - 1)sin(x)} \right) + \\ +(1-\beta)\delta^{\omega_1} \left(\frac{1}{(\gamma - 1)sin(\omega)} \right)^{\omega_2} \quad (3)$$

where δ is the distance, β is adaptive parameter, $\omega_{1,2}$ are the weight coefficients.

Distance refers to the total distance which the robot traveled during the fixed time interval. The second equation argument is responsible for changing the length of the robot, constants are omitted. Thus, these are the initial design parameters, which are optimized: γ, ω, q. The last parameter indirectly influences the cross-country passability.

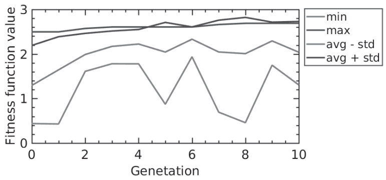
2) Develop optimization algorithm: In computer science, genetic algorithms are adaptive heuristic search algorithms based on evolutionary concepts. They represent an intelligent parallel exploitation of a design space and can be used to solve optimization problems, not necessarily optimizing, but often deriving near-optimal solutions.

For solving this task, the Deap [13] library was chosen, as it has all needed tools for implementing it. It has good API and documentation. This pseudo code provides the high-level description of overall algorithm.

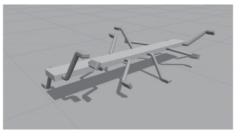
Algorithm 3: Overall high-level algorithm

```
Input: α – number of generations, β – number of individuals,
       γ – number of terrains
Output: Good enough parameters for robot
begin
    generate set of terrains;
    randomly initialize a first population of robots;
    for i = 0 to α do
        for j = 0 to β do
            distance = 0;
            for k = 0 to γ do
                start simulation;
                distance+ = cur_distance;
            end
            avg_distance = distance/γ;
            evaluate fitness function;
        end
        select the best parents;
        perform crossover on chosen parents;
        perform mutation;
    end
end
```

As a result of our work we got the following results: after 11 generations (200 individuals in an initial population), the best robot has 6 legs on each side (12 legs in total). The robot managed to walk 5.21 meters, while the initial population could walk less than 2. In the figure below (Fig. 11b) you can see the best robot found during the first phase. In the following figure (Fig. 11a), you can see the fitness improvement trajectories for the first phase of experiments, showing fitness max, min, avg + std, avg - std, across generations.



(a) Fitness function values for this simulation



(b) Best individual robot, which has compromise between number of legs and cross-country passability

Fig. 11. Results of simulation. Goal is to find a robot with maximum cross-country passability and with minimum length of the body

V. Conclusion

In this paper, we proposed a concept of a new Biomimetic Centipede Robot StriRus. We proposed new modification of legged locomotion, which combines RHex-like locomotion and the possibility to move in all direction without changing orientation. High fidelity CAD model was presented. Also forward and inverse kinematics were derived and algorithms were shared. The main novelty of this project is omni-directional locomotion. Conventional robots with this type of locomotion cannot move in all directions without manual change of its orientation.

To create body designs of centipede robots which can be tuned to different operational constraints, including various rough terrain types structural synthesis and angle optimization via kinematics was done. Finally our robot got 12 legs in total and 120 degrees angle between neighbor legs.

In future to verify the concept and implement control algorithms we are planing to build the prototype. Additionally we are expecting to analyze different leg types in order to ensure high robot performance in both simple and complex environments.

VI. Acknowledgment

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