공학석사 학위논문

Leg Propulsion Mechanism Design of a Lizard Inspired Robot

도마뱀을 모사하는 소형고속주행 로봇의
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Abstract

Based on a previous research that verified the effects of lateral undulation of a bipedal running lizard, *Callisaurus Draconoides,* a novel robotic system was proposed. For this novel robotic system, the leg mechanism that resembles the running characteristics of the real lizard is the most important component in successfully developing the robot. This study focused on the synthesis of a leg propulsion mechanism of a lizard inspired robot. As a first step, data from a running lizard was acquired by a motion captured video. The four bar mechanism was utilized in mimicking the trajectory of the feet of the lizard, and optimization scheme was applied to determine the optimal lengths of the links of the proposed mechanism. Finally, running experiment was carried out with the designed leg mechanism on a treadmill, concluded with a performance analysis

Keywords : biomimetic, lizard inspired robot, leg mechanism, four bar mechanism, design optimization,

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1 Introduction

1.1 Research background

The running patterns of vertebrates vary depending on the species. The development of these running patterns is known to be evolutionary result of adapting to the environment. As biologists use methods such as comparative approaches, engineers have put in effort to implement the natural behaviors into robotic systems to achieve better efficiency, stability and robustness.

The development of locomotive systems inspired from nature have been a very popular topic of research in the field of mechanical engineering. The VelociRoach robot developed by U.C Berkeley mimics the gait of the cockroach to realize a high speed running [1]. The Sticky Bot by Stanford utilizes the microstructure of the lizards' feet to climb up the wall [2]. The Cheetah Robot by MIT is inspired by the cheetah's high velocity running, and is under development [3]. These are the examples of inspiration from nature and as such, the question of this research arouse from the running behaviors of the lizard.

The key concept of the proposed lizard inspired robot is that with the lateral undulations of the body, the heading of the lizard robot is able to be controlled when running in high velocity. The verification of this concept was previously studied and published [4].

1.2 Previous study on the lizard's running

The previous study on the effects of lateral undulation of the lizard named *Callisaurus draconoides* is the fundamental idea behind developing the lizard inspired robot [4]. Through assumptions and logical development, this study focuses on how the S-shaped lateral undulation of the lizard's body effect the lizard's running.

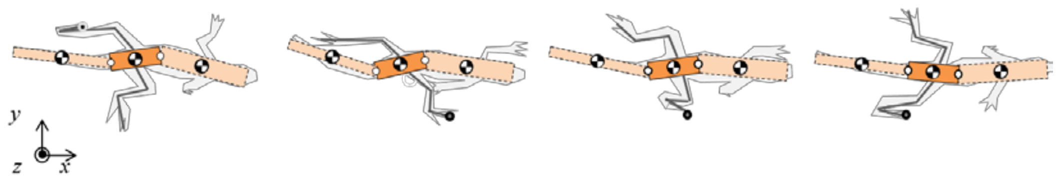

Figure 1.1 Schematic of the lizard's running with lateral undulation

The study's finding is that with the proper lateral undulation, the lizard is able to establish a stable high speed bipedal gait. More specifically the study showed that the need for Ground Reaction Moment (GRM) which is produced at the feet, is minimized when the lateral motion of the bodies exist. Due to the structural composition of muscles that also supports this conclusion, there is an anatomical study of the lizards' leg muscles that shows the Ground Reaction Force (GRF) will be dominant at the feet [5]. Due to these studies it was established that the leg mechanism will have to produce high magnitudes of GRF, and almost no GRM. Following the analyses of such target animal, a new concept of locomotive robot was proposed. With the findings of the effects of waist and tail movements, a locomotive device such that the yaw motion controlled high speed running was conceptually formed. The understanding of the lizard's behaviors forms the basis of this study and should be noted that the principles found are applied without prejudice.

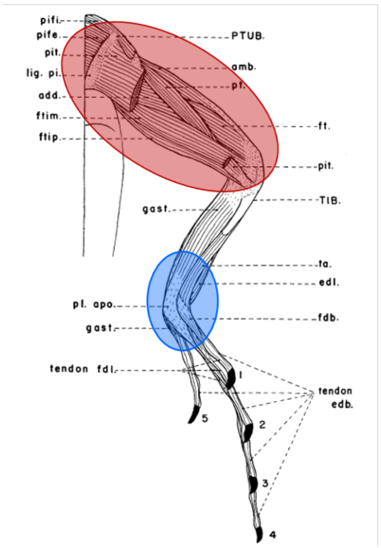

Figure 1.2 The anatomical composition responsible for Ground Reaction Moment (blue) and Ground Reaction Force (red)

1.3 Research goals and contributions

The particular species of lizard that is to be concerned with in this study is the *Callisaurus draconoides*. The species is characterized by its high running speed, bipedal gait and its lateral undulation of the bodies while running. As a previous study, the principles behind the running of these lizards were studied and a new robotic system was proposed encapsulating the discovered properties.

This study focuses on a very natural topic that will arise in realizing the proposed biomimetic lizard robot, which is the propulsion mechanism, namely the leg mechanism of the lizard robot.

The process of synthesizing the mechanism starts out by acquiring data from the real lizard running. The numerical data obtained during this step provides the target trajectory of the propulsion mechanism. The type of mechanism is selected for the realization of the high velocity foot propulsion mechanism. With the application of the optimization theory the design variables of the mechanism are determined. Finally, the computer aided design of the leg mechanism was produced, and was manufactured afterwards to be tested on a treadmill.

The purpose of this study was to provide a lizard inspired robot with an appropriate leg propulsion mechanism. In doing so, the synthesis of a running mechanism mimicking the lizard’s feet trajectory with a single actuator was proposed. The contribution would be a development of a high speed leg propulsion mechanism with an open loop control running, resembling that of the real lizard.

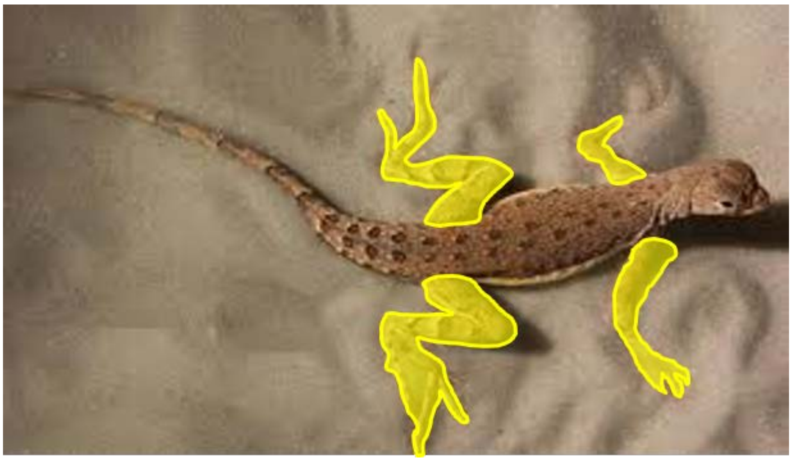

Figure 1.3 The target of this study: the leg propulsion mechanism of a lizard inspired robot

2 Analysis on the biomimetic target

The target of biomimetics of this study, *Callisaurus draconoides,* is thoroughly studied by many biologists. Irschick and Jayne studied the three-dimensional kinematics of the hindlimb in their paper [6]. Li et. al studied the foot use of the *Callisurus draconoides,* especially when they are in very swift movements.

Figure 2.1 Lateral, dorsal view of *Callisaurus draconoides'* running [6]

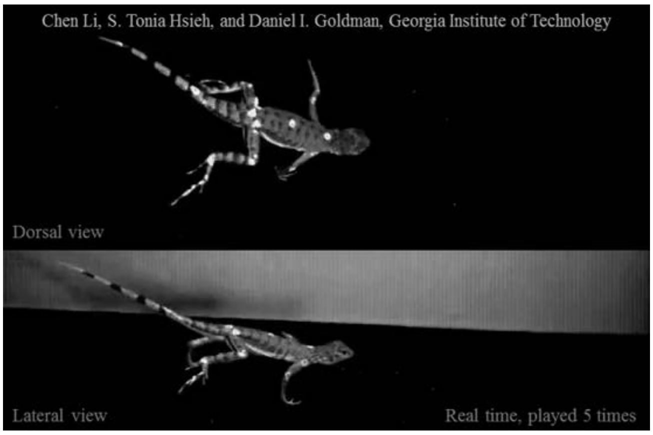

Figure 2.2 Study of multifunctional foot use of *Callisaurus draconoides* [7]

In many of these type of studies, *Callisaurus draconoides'* locomotive behavior can be characterized as having a very high frequency strides, fixed trajectory of the feet in every stride and a bipedal gait.

2.1 Running characteristics

The *Callisaurus draconoides* have been studied for a notable amount of time by many biologists. The physical dimensions are presented in Table 2.1 and Table 2.2 summarizes the running parameters of the *Callisaurus draconoides.*

Table 2.1 Physical dimensions of *Ca.draconoides*

Variable	*Ca. draconoides*
Snout vent length (cm)	7.6±0.45
Mass (g)	9.5±1.50
Tail length (cm)	10.1±1.13
Femur length (cm)	1.9±0.09
Tibia length (cm)	2.1±0.06
Tarsals and metatarsals length (cm)	1.3±0.05
Fourth toe length (cm)	1.9±0.10
Humerus length (cm)	1.6±0.07
Ulna length (cm)	1.2±0.06
Forefoot length (cm)	1.5±0.07
Pelvic width (cm)	0.9±0.05
Body width (cm)	1.6±0.11
Trunk width (cm)	4.4±0.22

Table 2.2 Running parameters of *Ca. draconoides*

Variable	*Ca. draconoides*
Speed (m/s)	4.0±0.1
% Strides digitigrade	75
Stride length (cm)	31.9±1.1
Step length (cm)	7.4±0.2
Stride width (cm)	5.1±0.4
Stride duration (ms)	80±3
Duty factor (%)	24±1

The target lizard has a total body length of approximately 190mm with the tail and legs at about 100mm each. The mass is around 10grams. It is know that his lizard can travel 4m/s which is 22.6 bodylengths/second. In relative scale speed wise, this makes the lizard one of the fastest animal on land. Compared to humans maximum speed, which is 4.5~5.5 bodylengths/second, such lizard is characterized by its swift movement when exposed to certain circumstances such as in situations with danger, hunting etc.

In terms of running parameters, this lizard has a stride length of approximately 74mm for every stride. Considering the fact that the total length of the body is 190mm this is relatively short compared to other animals.

However, to accomplish high speed running the lizard has a very high stride frequency, which is 12.5 Hz. Also, this fast running lizard changes the gait from trot at low speeds to bipedal at high speeds. It is known that at high speeds the front limbs are used for balancing and thus, both at high and low speed most or entire thrust is generated at the hind limbs. The duty factor, which is the contact time divided by the period of the stride, is 0.25, with the stride duration 80ms for every stride. Fig. 2.3 shows the snapshots of the *Callisaurus draconoides'* high speed running.

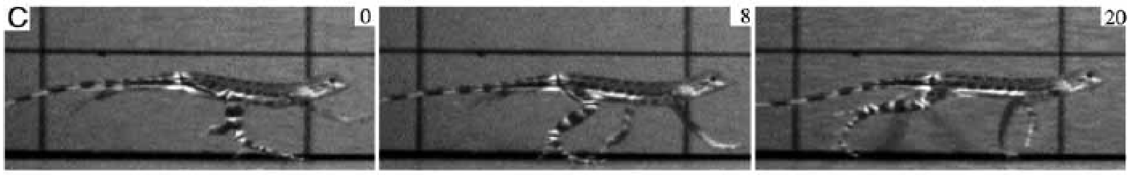

Figure 2.3 Snapshots of *Callisaurus draconoides'* running

The proposed concept of the lizard inspired robot will not be covered in this study. However it has been established that the robot will be composed of 3 bodies which are anterior body, posterior body and tail. It should also be noted that the leg mechanism will exert only ground reaction force in the direction parallel to the posterior body, as in Fig 2.4. Fig. 2.5 schematically labels the overall lengths and morphometric of the target lizard.

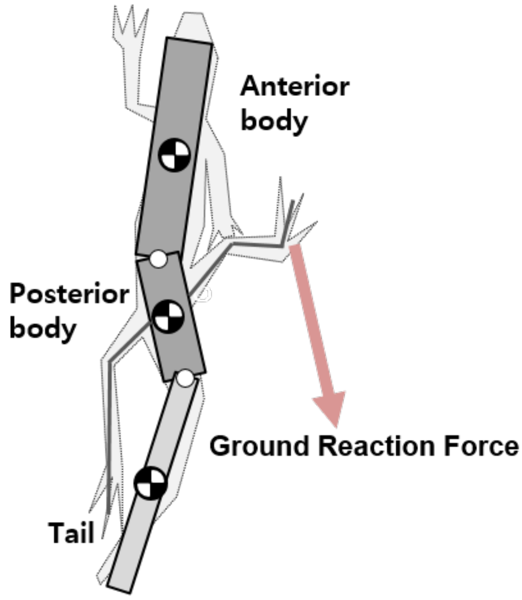

Figure 2.4 Bodies of the proposed robot concept and the direction of ground reaction force exerted

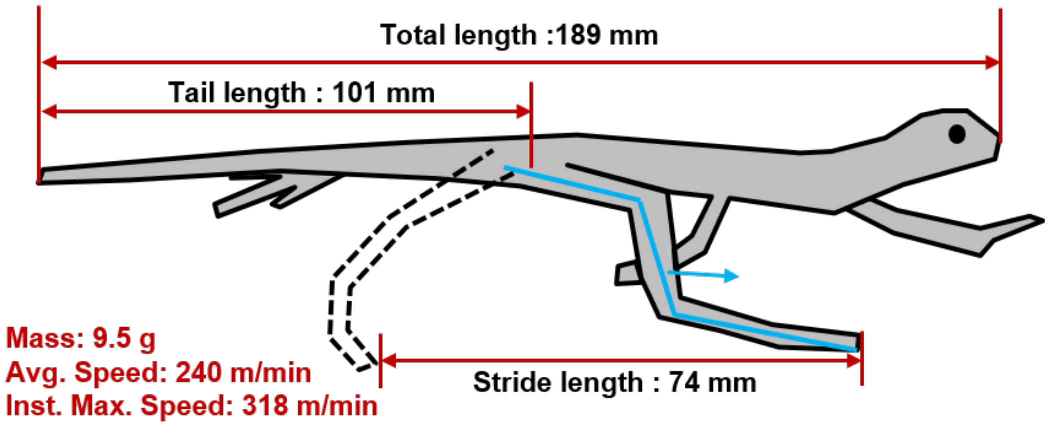

Figure 2.5 Schematic representation of the lengths and morphometric of the target lizard

2.2 Mechanism type for the leg

As previously mentioned, there are many robots developed, or under development that is aimed to devise a new locomotive device inspired from nature. For the synthesis of the leg mechanism there may be of two types. The first type is characterized by the movement of every joints, as shown in Fig. 2.6

Figure 2.6 Leg mechanism of Cheetah robot by MIT (left), Big Dog by Boston Dynamics (right)

For the mechanism of this type, the multi jointed leg with many actuators, each link imitates the real leg counterpart so the bidirectional movement of actuators is unavoidable. This fact makes the running speed of the mechanism slow, and subject to heavy control algorithms. However when controlled appropriately, it can produce very precise leg motion.

The other type of mechanism is of a multi or a single jointed structure with a single actuator. Jansen mechanism in Fig. 2.7 is an example of this type. What matters in these mechanisms type is only the endpoint trajectory at the end of the link. Thus, the unidirectional movement of actuator ensures high speed running, with less degree of freedom than the previous mechanism type. The purpose of this study is to devise a high speed leg propulsion mechanism with open loop control, and in doing so a mechanism of the type that employs unidirectional movement of actuators is more suitable. Accordingly one of the most reliable linkage structure, the four bar linkage as represented schematically in Fig. 2.8, was chosen to be used in the leg mechanism synthesis.

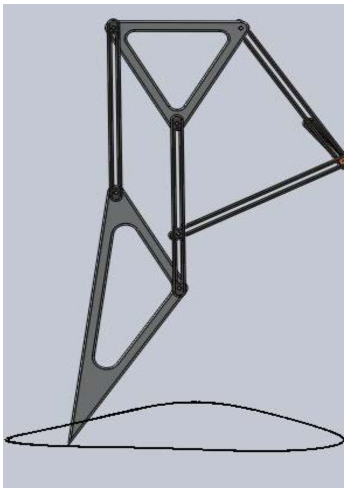

Figure 2.7 Jansen mechanism that uses only a single actuator

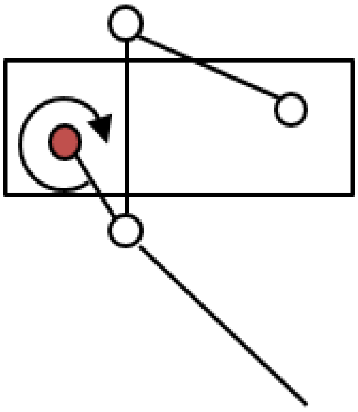

Figure 2.8 Schematic representation of a four bar linkage

The four bar linkage mechanism is used as a leg mechanism with the follower link acting as a leg part and provide propulsive force. The actuator rotates the input crank and creates a unidirectional, repetitive motion.

2.3 Leg motion extraction and function approximation

The feet trajectory of the lizard, *Callisaurus draconoides*, which is the data for the target being traced will have to be obtained before constructing a linkage mechanism. From the motion picture of the *Callisaurus draconoides* running, 23 data points of the feet trajectory were extracted by motion capture, as in Fig. 2.8.

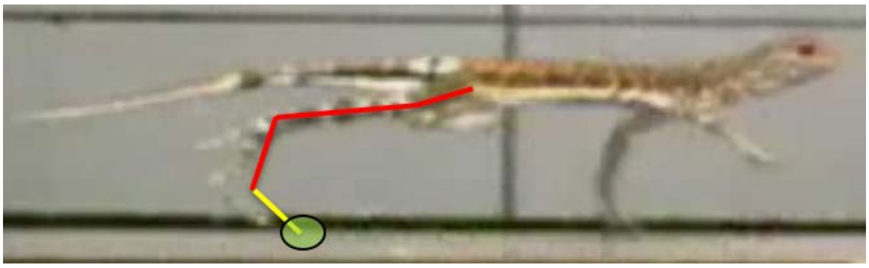

Figure 2.9 Feet trajectory motion capture (leg marked in red, feet marked in yellow and feet trajectory points in green circle)

Upon obtaining the reference points, the trajectory of the feet is needed to be approximated as a function because in order for the comparison of the end point trajectory of the mechanism continuous reference values are necessary. The end point trajectory approximation function was parameterized and is composed of two different frequencies of cosine functions and a sine function. The reason for having two different frequencies of cosine function is that when the curve approximation is completed, this had showed better results.

The parametrized approximation function of the trajectories are represented in Eq. (2.1) and Eq. (2.2), where A, B, C, D, E, F, G, H are the coefficients and phase constants of the functions.

$$\mathrm{X} = \mathrm{A}_1 \cos\left(\frac{\pi}{2}t + A_2\right) + B_1 \cos\left(\frac{\pi}{4}t + B_2\right) + C_1 \sin\left(\frac{\pi}{2}t + C_2\right) + D \tag{2.1}$$

$$\mathrm{Y} = \mathrm{E}_1 \cos\left(\frac{\pi}{2}t + E_2\right) + F_1 \cos\left(\frac{\pi}{4}t + F_2\right) + G_1 \sin\left(\frac{\pi}{2}t + G_2\right) + H \tag{2.2}$$

Utilizing the parametrized function, the coefficients that minimizes the following values in Eq. (2.3) and Eq. (2.4) were found, using the *fmincon* function in *Matlab*.

$$\sum (X_{ref} - X)^2 \tag{2.3}$$

$$\sum (Y_{ref} - Y)^2 \tag{2.4}$$

The obtained coefficients of the approximation function is given in Table 2.3. Also the plot comparing the reference trajectory and the approximated trajectory is displayed in Fig. 2.9. The R values for the X points showed 0.991 and for the Y points 0.989.

Table 2.3 Values of the coefficient of approximation function

Coefficient	Value
A_1	282.3
A_2	0.3673
B_1	58.96
B_2	0.0420
C_1	67.90
C_2	0.9645
D	1661
E_1	132.1
E_2	2.368
F_1	21.20
F_2	0.8552
G_1	13.93
G_2	0.5141
H	1910

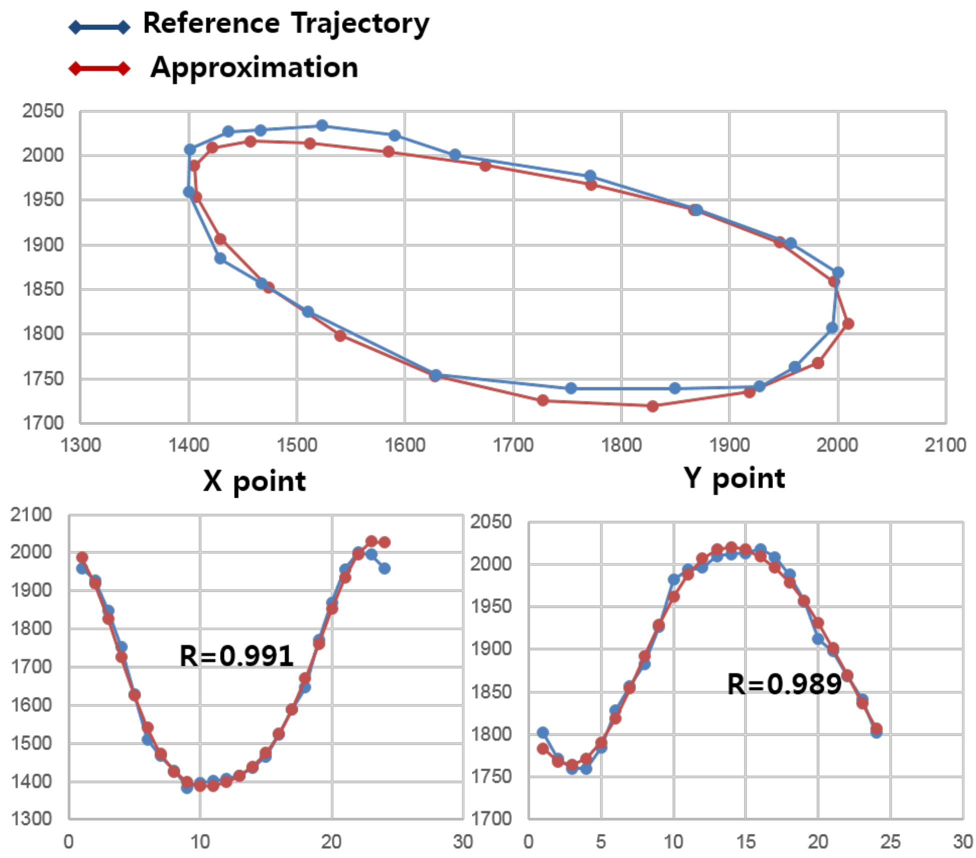

Figure 2.10 The comparison plot of the reference trajectory and the approximated trajectory

3 Mechanism synthesis

3.1 Design variables and constraints of four bar linkage

With the obtained function of approximated trajectory a four bar mechanism has to be constructed in a way that the end point of the linkage traces the reference trajectory correctly. As shown in Fig. 3.1, the four bar mechanism has total of 7 design variables.

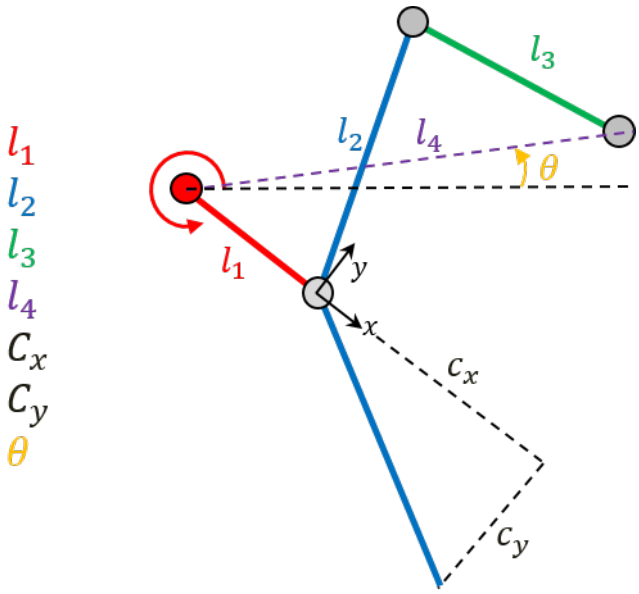

Figure 3.1 Design variables of the four bar linkage

l_1, l_2, l_3, l_4 are the lengths of input crank, coupler link, follower link and the ground distance respectively. The endpoint of the coupler link generates the feet trajectory. C_x, C_Y are the endpoint position measured from the input crank-coupler link joint. Θ is the amount of elevated angle between the input origin and follower link origin. To numerically find the optimal solution of the design variables, a *Matlab* simulation of the four bar linkage with its design variables and the generated endpoint trajectory was developed, as in Fig. 3.2.

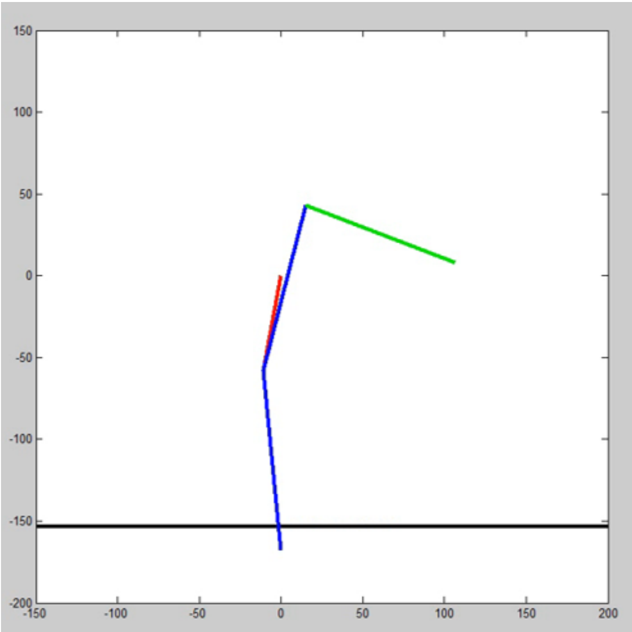

Figure 3.2 *Matlab* simulation of the four bar linkage endpoint trajectory

The combinations of the design variables will generate a working four bar linkage as far as the Grashof condition is kept. However since the leg mechanism is to be mounted on a lizard robot platform there are constraints regarding the occupying space of the mechanism and the relative size compared to the whole lizard robot. There has to be also a constraint related to the running parameters. Since the real lizard has a duty factor of 0.25 this will have to be satisfied in the mechanism. Also the inlet contact velocity v_{1x} and the outlet contact velocity v_{2x} has to be same with that of the real lizard, i.e. v_{2x} = 1.4 m/s and $v_{2x} - v_{1x}$ < 0.2 m/s. The geometrical constraints and the running parameter constraints are summarized in Fig. 3.3.

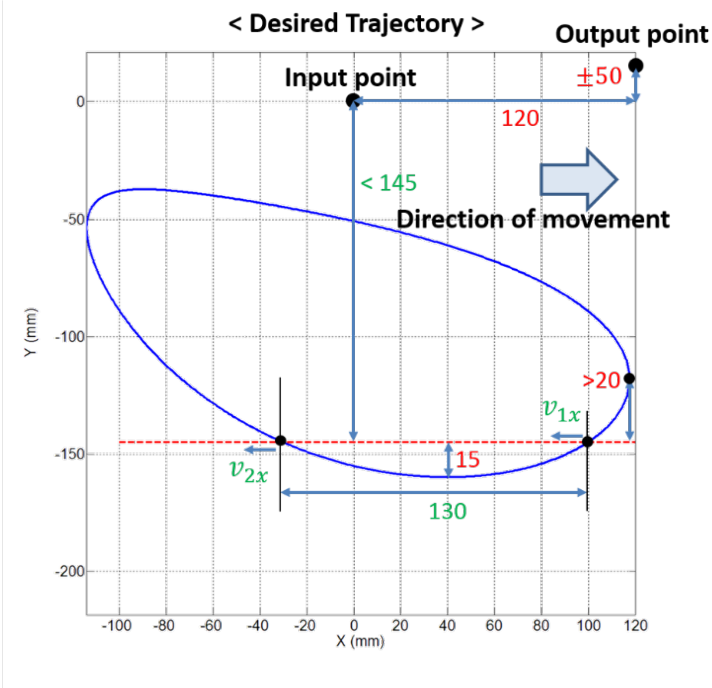

Figure 3.3 The geometrical and running parameter constraints of the four bar leg mechanism

3.2 Four bar linkage optimization

The optimization method used in this study is called Hybrid Taguchi Random Coordinate search Algorithm (HTRCA) [8]. This method has 2 steps of optimization. The first step utilizes the first derivative values of the reference and the created trajectory, which determines the shape of the trajectory. The first step of optimization expressed as follows:

$$\min_{X_{link} \in R^5} RMS(1^{st}\ deriv._G - 1^{st}\ deriv._D)$$

Subject to *Desired Shape*

$T_1, T_2, T_3 > 0$ → *Grashof Condition*

where:

RMS(C) : Root mean square of c

$n^{th}\ deriv._G$: n^{th} derivative value of created shape

$n^{th}\ deriv._D$: n^{th} derivative value of target shape

$$X_{link} = [l_2\ l_3\ l_4\ l_{cx}\ l_{cy}]/l_1$$

The second step of optimization utilizes the second derivative values to determine the size of the trajectory and is expressed as follows:

$$\min_{l_1 \in R} RMS(2^{nd}\ deriv._G - 2^{nd}\ deriv._D)$$

Subject to $$X_{link} = X_{link}^{*}$$

The advantages of using this algorithm is that this method is able to use a closed curve as a reference trajectory whereas in many other optimization algorithms this is not possible. Also this algorithm was proven to produce the results with very low failure rates compared to other algorithms. Moreover the fact that the velocity of the trajectory can be considered in the optimization process was the reason this method was used. Since the trajectory of interest is mainly the region of contact with the ground, the weighting factor of 1 to 3 was applied to the region of curves that is in contact with the ground and airborne respectively, so that the result will show a more targeted result to trace the trajectory in the contact region. The obtained trajectory is displayed in Fig. 3.4, and the design variables are shown in Table 3.1.

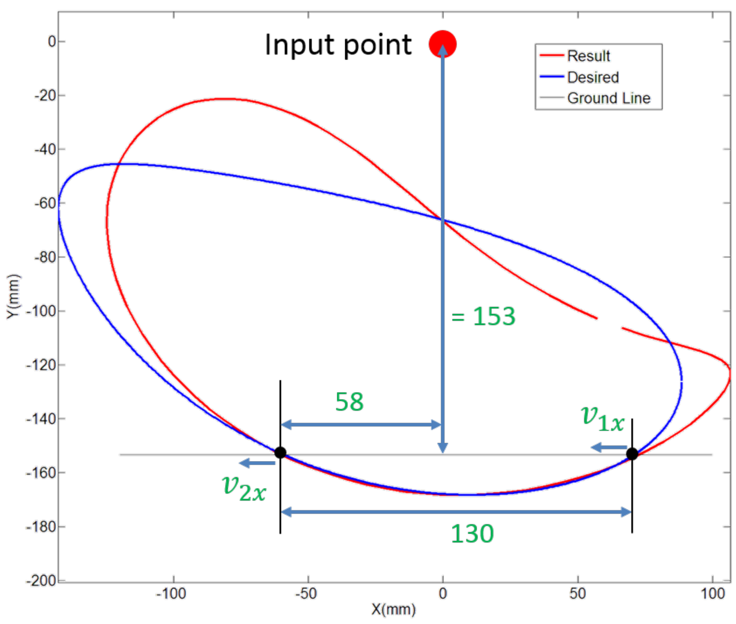

Figure 3.4 The optimization result (red) compared with the original lizard's feet trajectory (blue)

Table 3.1 Optimization result of the design variables

Design Variable	Value
l_1 (mm)	58.901
l_2 (mm)	104.059
l_3 (mm)	98.169
l_4 (mm)	107.004
C_x (mm)	-104.059
C_Y (mm)	-38.286
Θ (*rad*)	0.0734

3.3 CAD design of the overall structure

With the obtained design variables, a three dimensional CAD modelling of the leg mechanism was created using a *Solidworks 2014* software, shown in Fig. 3.5.

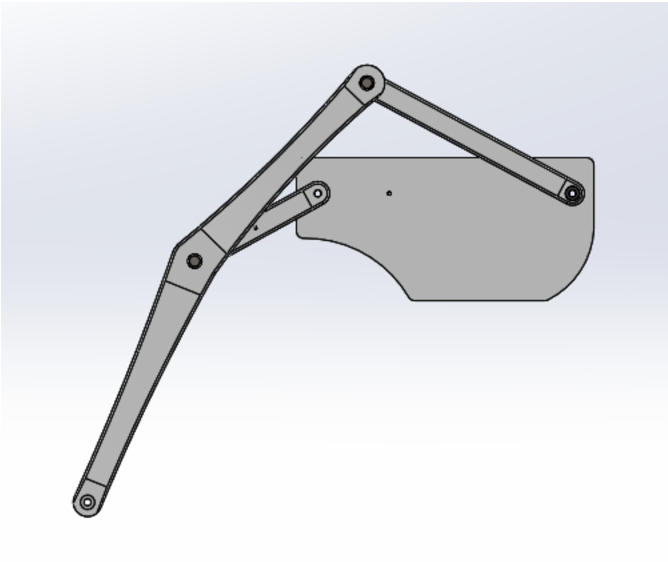

Figure 3.5 *Solidworks* modelling of a four bar linkage leg mechanism

The verification of Grashof condition, trajectory, any interference between the links and proper stride length was confirmed with the virtual model. In order for the leg mechanism to apply effective propulsive force to the ground, a compliance structure that absorbs or reduces the impact from the ground and the structure that is able to maintain contact with appropriate friction coefficient were necessary. As so, an ankle-feet mechanism was devised, with extra linkages on top of the four bar linkage, shown in Fig. 3.6.

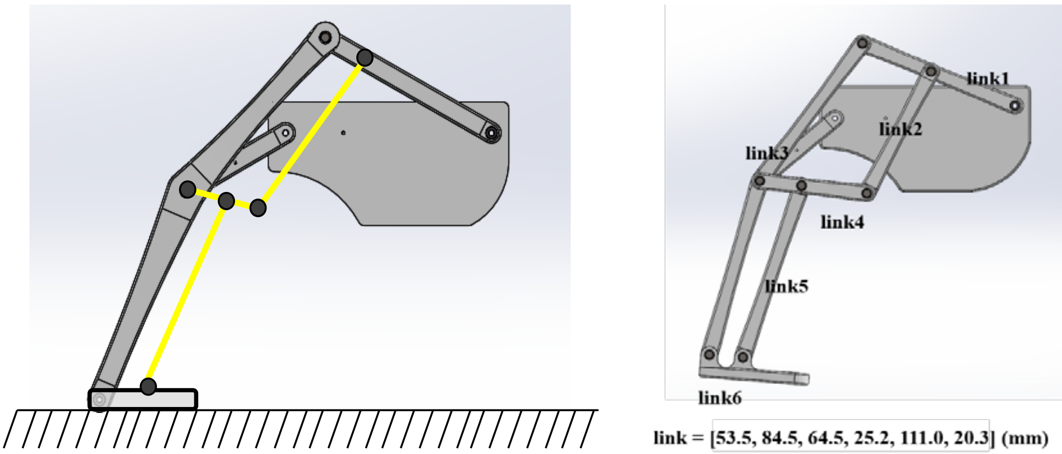

Figure 3.6 Ankle-feet mechanism for maintaining contact with the ground

The mechanism with extra linkages was simulated in *Matlab,* for tuning the linkages' length for the proper ankle angle in contact with the ground, as in Fig. 3.7.

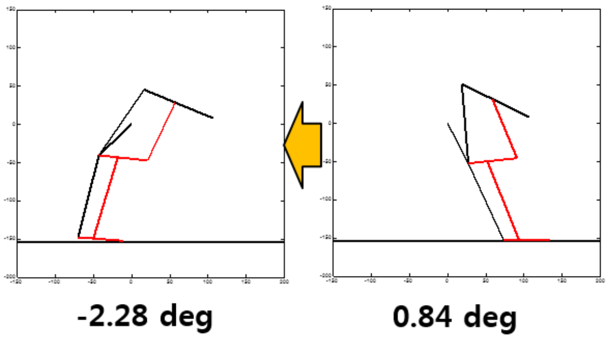

Figure 3.7 *Matlab* simulation of the ankle-feet mechanism

For the absorption of the impact, a double- wish bone compliant structure with shock absorbers was implemented between the leg mechanism and the main frame of the lizard robot, shown in Fig. 3.8.

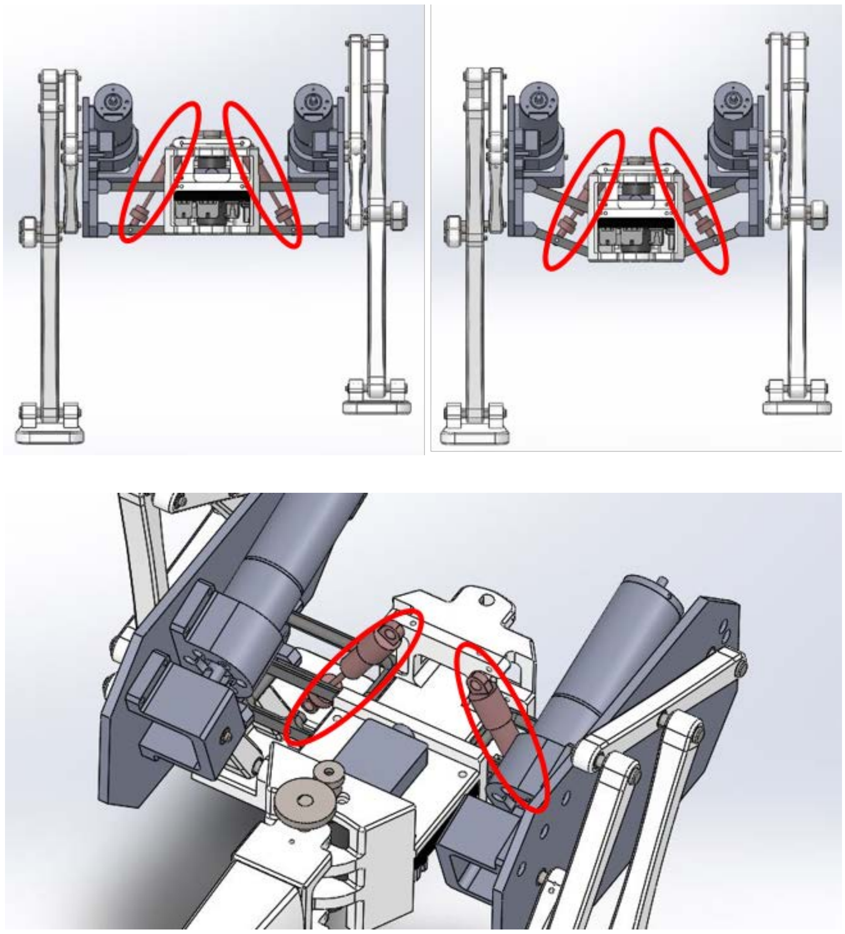

Figure 3.8 Double-wishbone compliant structure with shock absorbers highlighted

4 Prototype production and experiment

4.1 Prototype production

The prototype of the mechanism was manufactured with all of the design concepts proposed. One brushless DC motor was used for each leg and was placed longitudinally, using a bevel gear set to drive the input link. Aluminum alloy was used in parts where the rigidity of the structure is necessary, and the remaining parts were fabricated using the rapid prototyping polymers.

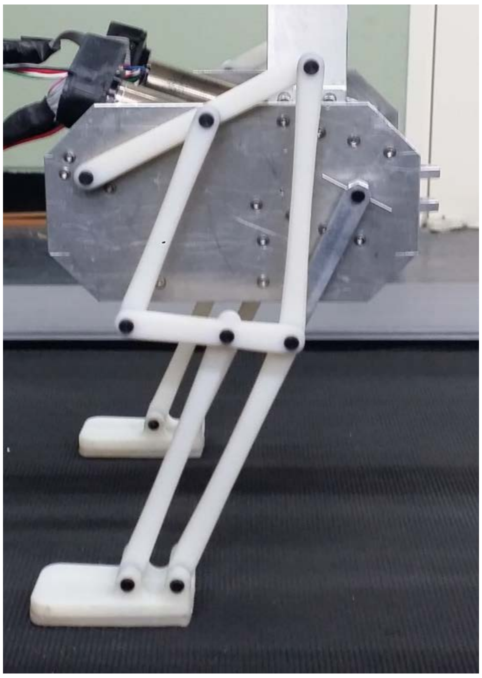

Figure 4.1 Prototype of the leg mechanism

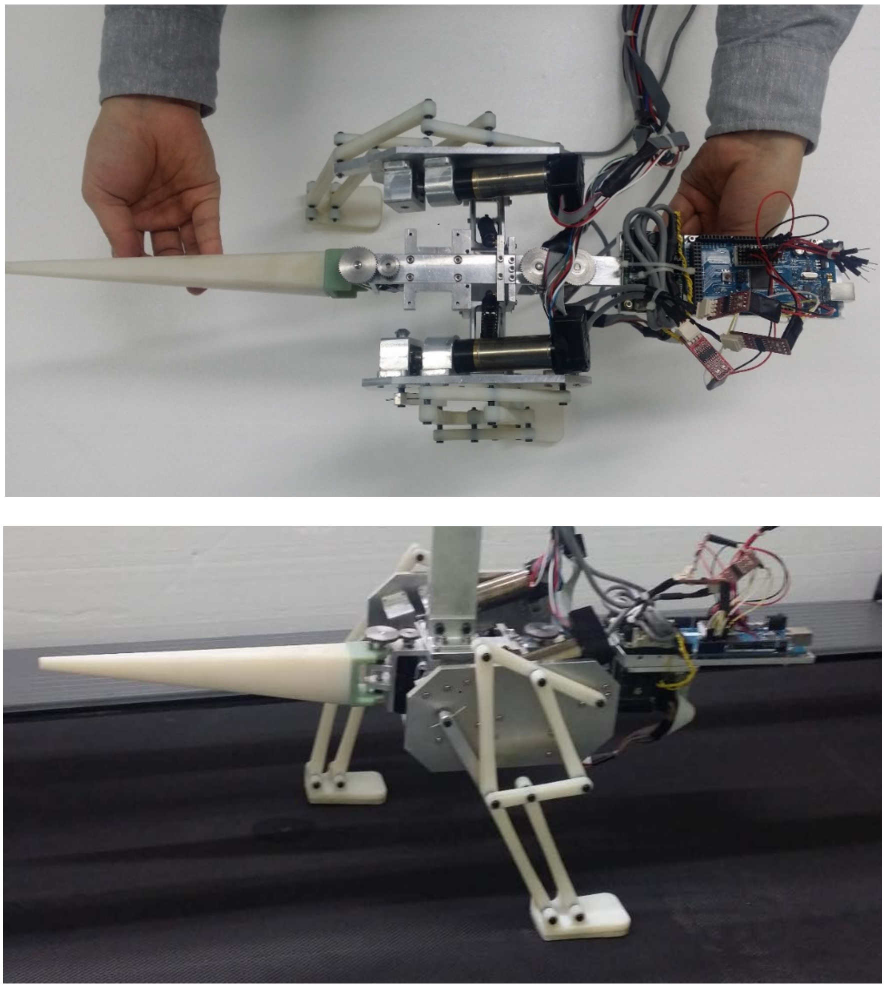
Figure 4.2 Lateral view (above), Top view (below) of the leg mechanism joined with the main frame of the lizard robot

The weight of the leg mechanism is 1.8 kg including the motor and control boards. The width of the leg mechanism is 210mm, height 200mm and 150mm long. The power source was placed externally.

4.2 Test bench setup

The test bench to test the leg mechanism's running was designed with aluminum profiles, linear motion guides and a tread mill. The test bench constrains the leg mechanisms motion in a sagittal plane.

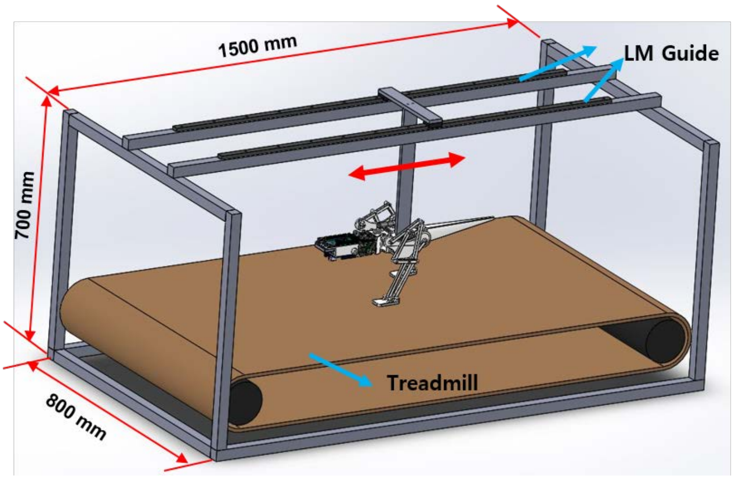

Figure 4.3 Dimensions of the test bench design

Figure 4.4 Manufactured test bench

4.3 Leg mechanism drive experiment

The leg mechanism prototype was experimented on a treadmill, and in doing so the speed of the treadmill was manually controlled in accordance with the leg mechanism speed.

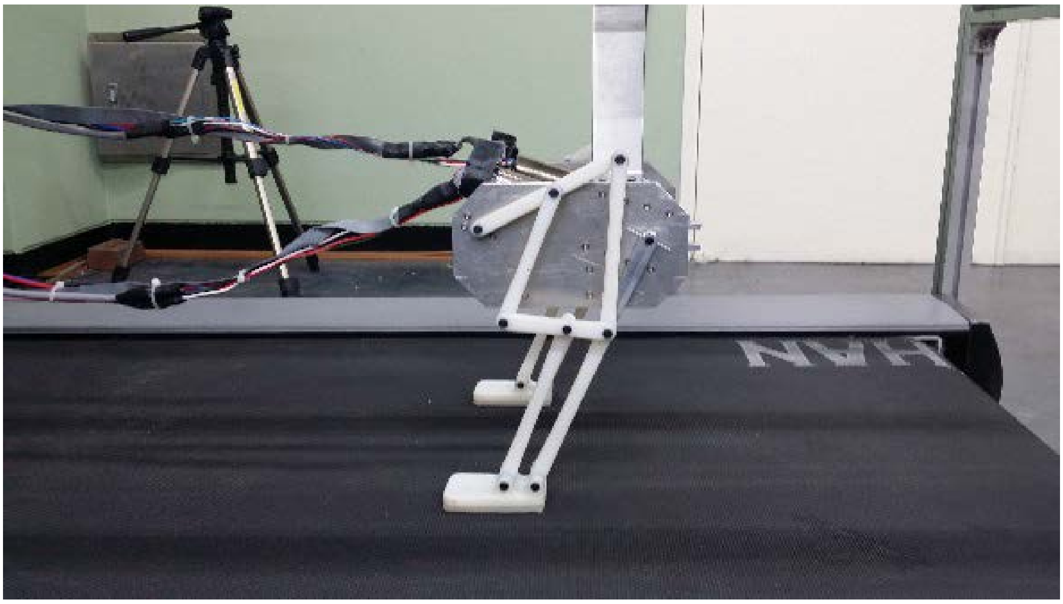

Figure 4.5 Experiment setup of the prototype

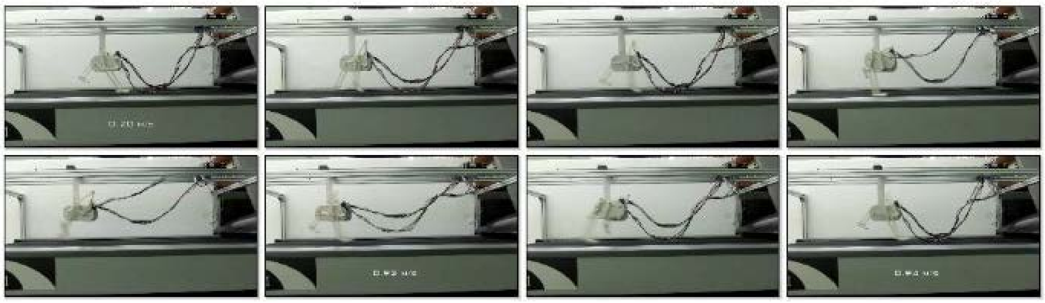

Figure 4.6 Snapshots of the experiment

With the both legs in operation, the leg mechanism achieved 60m/min of speed, or in relative scale wise, 6.7 bodylengths/second. A higher speed is possible with more rigid composite materials, considering the strength of material of the aluminum alloy and rapid prototyping polymers.

5 Conclusion

The objective of this study was to devise a leg mechanism of a lizard inspired robot. A four bar mechanism was used for the synthesis of a leg mechanism with high speed and open loop control. The feet trajectory of a target lizard, *Callisaurus draconoides*, was motion captured from a video and this was approximated as a function to provide continuous reference points. Four bar linkage optimization followed after, with the geometrical and running parameters constraints satisfied. With the optimization result, the design variables of the four bar linkage were decided and a virtual model of the leg mechanism was constructed. For the effective propulsion of the leg mechanism a feet-ankle structure and a compliant structure were added to the system. Fabrication of the concept were done with rapid prototyping and for the parts that high rigidity is required, aluminum was used. An experiment setup that is constrained in the sagittal plane with a treadmill was constructed. The experiment result showed approximately 60m/min or 6.7 bodylengths/second with the possibility of achieving higher speed with stronger materials.

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Abstract in Korean

본 연구는 도마뱀이 고속주행 시 보이는 요 움직임의 효과를 증명한 사전연구로부터 이 도마뱀을 모사한 로봇의 다리 추력 발생장치의 설계를 다루고 있다. 먼저 대상 도마뱀의 움직임을 관찰하여 도마뱀의 주행특성에 관하여 분석을 하고, 이 도마뱀이 주행 시에 보이는 발끝 궤적을 추출하였다. 추출된 궤적을 함수로 근사하여 연속적인 기준점을 만들었고 이를 토대로 4 절 링크의 최적화 설계 방법론을 이용하여 설계 변수를 정하였다. 선정된 설계 변수로 CAD 모델링을 진행하였고, 추가적으로 다리 추력발생 매커니즘이 효과적으로 작동될 수 있도록 발목, 발바닥 장치와 충격흡수 구조를 설계하였다. 설계안의 제작은 쾌속조형장비를 이용하여 제작하고 강성이 필요한 부분에는 알루미늄을 가공하여 사용하였다. 실험은 트레드밀 위에서 수직평면상으로 고정 시켜 진행하였으며, 실험결과 주행속도는 60m/min, 상대적 속도로는 6.7 몸체길이/초 를 달성하였다.

주요어 : 생체모사, 도마뱀 로봇, 다리 메커니즘, 4절링크, 설계 최적화

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