DESIGN AND ANALYSIS OF SNAKE ROBOT LOCOMOTION USING ARTIFICIAL SNAKE SCALE

BY

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ABSTRACT

The amazing locomotion capability of natural snakes is the central essence of this research. Among the four-basic kind of locomotion, the serpentine locomotion gives the snake fastest and comfortable journey towards the destination. Snake robots are mainly designed and developed based on the assumption of frictional anisotropy of the ventral scales and sequential use of the muscles to move the body in a harmonic sinusoidal pattern. Very few works have been carried out on the effect of scales on the motion of the snake robots, specifically the effect of geometry of the scales. Thus this research tried to explore the effects of artificial snake scales and their geometry on the motion of snake robots. The research started with the study of the serpentine locomotion of a real snake. The subject of the investigation was a *Python Reticulatus,* a young python at an age of 10 months. A simple setup was designed and fabricated to study different locomotion parameters from the real snake. The study proved the previous literatures and thus showed a way to work on a robot. Afterward different types of snake scale were designed and a mechanism to extract the force data from the scale was developed. The scales along with the force sensing system were attached at the ventral side of a nine link snake robot. The motion and force data of the snake robot were then acquired while running in a test bed. The robot was operated on three different types of surfaces: floor mat, engine gasket, and artificial leather. Analyses of the data revealed that uniform friction in all directions gives some insignificant motion of the robot without any predicted path. Whereas higher frictional anisotropy gives the robot more definite direction of movement. It is also found that significant anisotropy, especially higher lateral friction, gives more stability in direction. On the other hand, reduction in forward friction gives faster forward movement to the robot. This finding conformed to the results of energy consumption. It was also found that small scales at the lateral edges of the robot body contribute to the effective forward motion of the robot while such scales covering small area on the central line do not give any motion along the direction of the robot except lateral oscillation. Thus, this research leads to further improvement in scale characteristics of the robot to reach an optimum point of speed, energy consumption and accuracy.

خلاصة البحث

تعدّ القدرة المدهشة لحركة الثعابين الطبيعية الجوهر المركزي لهذا البحث. ومن بين أنواع الحركة الأربعة الأساسية للثعابين تعطي الحركة الموجية رحلة أسرع وأكثر راحة نحو الهدف. تصمّم الروبوتات الثعبانية عادة وتطوّر بناء على أساس افتراض التباين الاحتكاكي للحراشف البطنية بالإضافة إلى الاستخدام المتسلسل للعضلات لتحريك الجسم في نمط جيبي متناسق. هناك عدد قليل جداً من الدراسات التي تناولت تأثير الحراشف على حركة الروبوتات الثعبانية، وخصوصاً تأثير هندسة الحراشف. لذلك فقد حاول هذا البحث استكشاف تأثير الحراشف الاصطناعية وهندستها على حركة الروبوتات الثعبانية. بداية، تطرق البحث إلى دراسة الحركة الموجية للثعبان الحقيقي. وكان الثعبان موضوع الدراسة هو (بيثون ريتيكولتوس)، وهو ثعبان صغير يبلغ من العمر عشرة أشهر. وتم تصميم نموذج بسيط وتصنيعه لدراسة المعاملات المختلفة للحركة باستخدام الثعبان الحقيقي. وقد أثبتت الدراسة صحة الدراسات السابقة، وبالتالي أظهرت طريقة للعمل على هذا النوع من الروبوتات. بعد ذلك صُمّمت أنواع مختلفة من حراشف الروبوت الثعباني كما طوّرت آلية لاستخراج بيانات القوة من خلال هذه الحراشف. حيث أرفقت الحراشف جنباً إلى جنب مع نظام استشعار القوة في الجانب البطني من الروبوت الثعباني ذي الوصلات التسع. ثم تلا ذلك الحصول على بيانات الحركة والقوة للروبوت الثعباني أثناء سيره على أرضية الاختبار. خلال هذه الدراسة تم تسيير الروبوت على ثلاثة أنواع مختلفة من الأسطح: حصيرة أرضية، وسطح كأطواق المحرك، وسطح من الجلد الاصطناعي. وقد أظهرت تحليلات البيانات أن الاحتكاك المنتظم في جميع الاتجاهات يؤدي إلى حركة ضئيلة للروبوت في مسار غير متوقع، في حين أن احتكاكاً ذا تباين أعلى حسب الاتجاه يعطي للروبوت حركة ذات اتجاه أكثر تحديداً. وقد وجد أيضاً أن التباين الاحتكاكي الملحوظ، وبخاصة الاحتكاك الجانبي العالي، يعطي مزيداً من الاستقرار في اتجاه الحركة. من ناحية أخرى، فإن تقليل الاحتكاك الأمامي يعطي الروبوت الثعباني حركة أمامية أسرع. وتتفق هذه النتيجة مع نتائج قياس استهلاك الطاقة أثناء التجربة. وقد وجد من خلال الدراسة أيضاً أن استخدام الحراشف الصغيرة في الحواف الجانبية للروبوت يسهم في حركة أمامية فعالة للروبوت، في حين أن استخدام مثل هذه الحراشف على طول الخط الأوسط أسفل الروبوت لا يعطي أي حركة في الاتجاه الأمامي للروبوت باستثناء التذبذب الجانبي. وبالتالي فإن هذا البحث يؤدي إلى مزيد من التحسين في الخصائص المطلوبة لحراشف الروبوت الثعباني للوصول إلى نقطة التقاء بين كل من سرعة الحركة ودقتها وكمية الطاقة المستهلكة.

APPROVAL PAGE

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DECLARATION

I hereby declare that this thesis is the result of my own investigation, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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This thesis is dedicated to

my beloved parents, wife and daughter

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LIST OF ABBREVIATIONS

2D	Two dimensional
3D	Three dimensional
A, *B*	Arbitrary Constants
A/D	Analog-to-Digital
ABS	Acrylonitrile-Butadiene-Styrene
CCW	Counter Clockwise
CG	Center of Gravity
CW	Clockwise
Cyl	Cylinder
EEPROM	Electrically Erasable Programmable Read-Only Memory
I/O	Input/Output
I^2C	Inter-Integrated Circuit
ICD	Interface Control Document
PIC	Peripheral Interface Controller
PWM	Pulse Width Modulation
SPI	Serial Peripheral Interface
Surf	Surface
Thr	Thread
UART	Universal Asynchronous Receiver/Transmitter
USART	Universal Synchronous/Asynchronous Receiver Transmitter
USB	Universal Serial Bus

LIST OF SYMBOLS

ϑ	Mass per unit length
β	angle to the right of the axis of segment III of a three segment system
ω	Angular velocity
τ	Period of undulation
$\acute{L}_1,\ \acute{L}_2,$	Final length of the elastic material on two sides of the push point.
M_{r_1}, M_{r_2}	A rigid element, capable of sustaining tension without change in length
$\ddot{X}$	Acceleration
α_i	The initial winding angle
θ_i	The angles of each segments
μ_b	Friction coefficient in backward direction
μ_f	Friction coefficient in forward direction
μ_t, μ_l	Friction coefficient in transverse/lateral direction
a, b, c	Constants
F	Propulsive force
f	Initial force
f_{fric}	Friction force
$\boldsymbol{f}_{\text{int}}$	Inertial force
k	Stiffness of the material
K_n	The number wave shape
L	Snake body length
L_1, L_2	Initial length of the elastic material on two sides of the push point.
M_L	Elastic element on the left side
M_R	Elastic element on the right side

N	Normal force
P_1, P_2, P_3	Peg 1, Peg 2 and Peg 3
R_1, R_2, R_3	Reaction forces on segment 1, 2 and 3
S	The body length along the body curve of the robot
L_1 to L_4	Left sensor 1 to 4
R_1 to R_4	Right sensor 1 to 4
T	Torque
t	Time
V	Velocity
α	angle on the right of the axis of segment II
ψ	Tangential angle
θ	Angle between initial and final orientation of the robot

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Allah Subhanahu-wa-Ta‘ala is the maker of the most optimized systems. Among these systems, He gave the snakes the most versatile characters of locomotion. This especial criterion attracted the researchers to build snake robots using their ability to move through difficult terrains and spaces.

Over two decades, scientists have been working on snake robots to incorporate the abilities of a snake inside the robot and to have a robust machine. Pipes or any other narrow space is not a problem for a real snake to get into. They can also climb trees, walls, and cracks and can move over sand, rock, and so forth. Thus, a snake robot, with the features that a natural snake has, will be able to access through pipes or passages that are even more critical for inspection or any other purpose. Moving through the throat of a patient for assisting surgery (Simaan, 2004 and Simaan, 2006), for example, or working explicitly in search and rescue (Chowdary, 2012, Erkmen, 2002, and Kamegawa, 2005), fire-fighting missions are some of the attractive applications of snake robots that are being expected.

Until today, the ability of locomotion and adaptation to the situation of the biological snakes is far beyond of the robotic ones. These creatures have consecutively linked segments with multiple degrees of freedom, which make the snake robot more complicated to design and control. On the other hand, the snake scale gives the snake like creatures a unique movement, ability to climb up, and aptitude to move through tricky terrains and the story of the efficiency and compliance, which are probably hidden in these features.

The curiosity on snake locomotion is not new. Sixty years ago, in 1946 a British zoologist Gray, J. (Gray, 1946) carried out a pioneering work by analyzing the snake locomotion while Gray and Lissmann (Gray, 1950) worked on kinetics of snake locomotion, long before scientists thought to build snake robots. Gray illustrated the method of locomotion (serpentine) of the real snakes, where he found that despite of having no limbs snakes can move as efficiently as the limbed animal by using their body and belly scales and sequential movement of their muscles. Snakes give the fastest movement when moving in serpentine mode (Mosauer, 1932; Liljebäck *et al.* 2013). In this case, they make a sinusoidal wave in their body through contracting their muscles at the inner side of the curve. This contraction results in two components of forces, transverse and forward. The reaction force from the belly scales nullifies the transverse component of the force, as the belly scales have a very high lateral frictional coefficient. The remaining forward component of the force is used to move the snake forward. Gray also described three more types of locomotion, as snakes have four basic locomotion methods; those are Concertina, Crotaline or Side-winding, and Rectilinear. However, he explained the serpentine method explicitly, which is also the focal point of this research.

After Gray, several works on real snakes have been carried out that put light towards the journey of developing the robotic creatures. Hu *et al.* (Hu 2009) analyzed the snake motion experimentally and mathematically that confirmed the findings of Gray. He showed that the snake scale has frictional anisotropy that helps the snake move. He found that snake scale has minimum friction while moving forward, has a greater friction in backward slipping, and attains maximum friction in transverse direction, which also goes with the theory given by Gray. Moreover, his mathematical simulation shows the force and its direction applied by the snake during lateral undulation. As the muscles are the actuators for the animals for the movement of the body, snakes use them together with their scale property.

Jayne (Jayne, 1988a and Jayne, 1988b) investigated the muscular mechanisms for serpentine, side winding, and concertina locomotion, among which one full paper was on the serpentine motion. He experienced the same thing that Gray described. During lateral undulatory locomotion, "the segments of three muscles (Mm. semispinalis-spinalis, longissimus dorsi, and iliocostalis) usually show synchronous activity. Muscle activity propagates posteriorly and generally is unilateral. With each muscle, large numbers of adjacent segments (30 to 100) show simultaneous activity. During terrestrial undulation, muscle activity in a particular region begins when that portion of the body has reached maximal convex flexion and ends when it is maximally concave; this phase relation is uniform along the entire snake". This is exactly what Gray explained in his paper. Miller developed a simulation based on motion dynamics of snakes and worms (Miller, 1988).

The above were a few stories on real snakes but the robotic chronicle of snakes started in the year 1993, written by Hirose, S. (Hirose, 1993), giving the initial idea of locomotion of such robots. After Gray and Hirose, many researchers worked on the kinematics of snakes and robots. For example, Jayne and Davis (Jayne, 1991) worked on the kinematics and performance capability of concertina locomotion showing that the speed and the tunnel width are closely related; Kyriakopoulos, Migadis, and Sarrigeorgidis (Kyriakopoulos, 1999) also worked on kinematics, design, and motion planning of snake robots. On the other hand, Prautsch and Mita (Prautsch, 1999) developed the theoretical base of the dynamical position control of snake robot.

Khan *et al.* (Khan, 2010) worked on snake scales that helped the snake robots to move more like real snakes and to the best of the author’s knowledge, it was the first scale-based work ever. Snakes use serpentine motion when they move fast. However, in case of narrow spaces to move through, snakes change their strategy. Thus Khan *et al.*, adopted a novel method of locomotion and a new kinematic analysis with a minimum number of links, as minimum as with two actuators.

After Khan *et al.*, Marvi *et al.* (Marvi, 2011) designed and developed a robot using adjustable snake scale named SCALYBOT. They introduced it as a snake inspired robot, not as a snake robot, that gives concertina locomotion by joining and controlling several modules like that can make a complete snake robot with snake scale. Farther, Marvi, and Hu (Marvi, 2012) analyzed the concertina locomotion through narrow channels. They measured the frictional properties and found that snakes use transverse force on channel wall and dig their scales to double the friction. Thus, the work of Khan *et al.* and Marvi *et al.* shows promising prospect in locomotion of snake robots using snake scale. Moreover, it seems that attaining the highest speed, climbing slopes, moving through challenging terrains, and combating unexpected situation would be possible more efficiently by using a scale based snake robot.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

The ability of today’s snake robots is still like the infants who are learning how to move compared to the real ones. Real snakes have versatile locomotion capability of moving through rough terrains due to the methods of locomotion and the scales underneath their body. Snake robots using wheels for locomotion may give faster movement but it goes against the ability to have versatile locomotion to move through obstacles as well as the climbing ability of the real snakes. At present, no snake robot is using serpentine locomotion with the aid of ventral scale. Analyses on snake scales is very shallow to help design snake robots with the capabilities of the real snakes. Lack of proper knowledge of the snake scales and consequent serpentine locomotion of the snake requires extensive investigation for designing efficient snake robots with versatile capabilities of the real snakes.

1.3 RESEARCH PHILOSOPHY

To achieve the serpentine or lateral undulation locomotion capabilities of the real snakes, snake robots need to mimic the structural and motion characteristics of the real snakes. Real snakes are able to move faster while executing serpentine gait using snake-scales underneath the body. Thus, a snake-scale based structure of a snake robot with serpentine gait is more likely to achieve faster and efficient motion.

1.4 RESEARCH OBJECTIVES

The objectives for acquiring knowledge on snake scale and snake motion have been set as follows:

1. To develop a prototype of a snake robot with different artificial snake-scale.
2. To develop a test bed for acquiring motion and force data of the snake robot.
3. To evaluate the performance of the snake robot against the different snake-scale parameters.
4. To develop correlations among the different parameters of the snake robot based on serpentine motion.