Design and control of a soft, shape-changing, crawling robot

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Abstract—Soft materials have many important roles in animal locomotion and object manipulation. In robotic applications soft materials can store and release energy, absorb impacts, increase compliance and increase the range of possible shape profiles using minimal actuators. The shape changing ability is also a potential tool to manipulate friction forces caused by contact with the environment. These advantages are accompanied by challenges of soft material actuation and the need to exploit frictional interactions to generate locomotion. Accordingly, the design of soft robots involves exploitation of continuum properties of soft materials for manipulating frictional interactions that result in robot locomotion. The research presents design and control of a soft body robot that uses its shape change capability for locomotion. The bioinspired (caterpillar) modular robot design is a soft monolithic body which interacts with the environment at discrete contact points (caterpillar prolegs). The deformable body is actuated by muscle-like shape memory alloy coils and the discrete contact points manipulate friction in a binary manner. This novel virtual grip mechanism combines two materials with different coefficients of frictions (sticky-slippery) to control the robot-environment friction interactions. The research also introduces a novel control concept that discretizes the robot-environment friction interaction into binary states. This facilitates formulation of a control framework that is independent of the specific actuator or soft material properties and can be applied to multi-limbed soft robots. The transitions between individual robot states are assigned a reward that allow optimized state transition control sequences to be calculated. This conceptual framework is extremely versatile and we show how it can be applied to situations in which the robot loses limb function.

Index Terms—soft robots, biomimetic, shape memory alloys, locomotion, friction, variable friction mechanism, model-free control

I. INTRODUCTION

Soft materials in nature allow animals to interact and adapt to uncertain and dynamically changing environments. The extraordinary versatility of soft structures is visible in the locomotion of worms and caterpillars or in manipulation by octopus and elephant trunks. Soft materials also play a major role in the performance of animals with stiff articulated skeletons by providing joint compliance, elastic energy storage, impact resistance and reliable limb-to-surface contact regimens [1]. Motivated by the robustness and adaptability of living systems there is increased interest in developing bio-inspired soft robots [2–7]. Introducing softness into robot designs makes them safe for operation, increases their range of movement and improves their performance in complex environments. However, soft materials also create design challenges that are different from those of traditional “rigid/hard” engineering.

Consequently, it is essential to explore and elaborate a novel set of design and control principles that help to bridge a gap between hard and soft engineering approaches [8].

Terrestrial locomotion of robots using undulatory motion [9–13], compliant limbs [7, 14] and soft bodies [2, 15, 16] have been important topics in the field of bioinspired robotics. This research presents the design of a robot inspired by caterpillars using a soft deformable body with discrete contact points between the robot and the environment. The platform is modular, allowing it to be expanded to test problems of increasing complexity. In this paper we present some design considerations for a bioinspired robot, introduce a novel state transition control for the soft robot and conclude with a discussion of the experimental results and significance of our findings.

II. DESIGN OF MODULAR SOFT

A. Design challenges

The two key challenges to designing soft robots capable of locomotion are frictional interactions and soft actuation.

Frictional interactions. A major factor in effective terrestrial locomotion is the changing contact between the body and its environment. The forces required to initiate or maintain differential movement between interacting surfaces are often dominated by friction. Animals have evolved a variety of mechanisms to exploit these forces including directionally sensitive friction [17], adhesives [18], structures that exploit asperities in different size ranges [19] and deployable or retractable grippers [20, 21]. In general, locomotion results from optimization of frictional forces by minimizing friction at one end while maximizing it at the other [22]. The gripper-like variable friction mechanism, discussed in Section II-C, achieves a similar effect using two materials with different...
Actuation of soft robots remains a challenge because most electromagnetic systems are made of hard materials [23]. Alternative systems such as dielectric elastomeric actuators (DEAs) have been explored [24, 25], but these require high voltages for actuation and, without a rigid frame, produce very low stress [26]. Other flexible actuators include pressurized liquid or air [15, 27, 28] and cable-driven systems [5]. The platform described here uses shape memory alloy (SMAs) coils to amplify the overall strain [3, 5, 16, 23]. These are activated through resistive heating which causes them to contract. Analogous to natural muscles, re-extension requires an external force which is provided by another SMA coil or intrinsic elasticity of the deformed body. Typically, the soft actuators are embedded inside the soft body to provide it the dual actuator-structure function. Apart from type of actuation, the design of actuation also needs to ensure controlled deformation of the soft material body.

**B. Robot body and actuation**

With these design features in mind we introduce a new platform for soft robotics research. The soft robot design incorporates structural control, friction manipulation, soft actuation using minimum actuators and a monolithic body. The design is modular and can be used to build robots with increased structural complexity. This will facilitate systematic analysis of robust control strategies for highly deformable robots. The basic module of this robot is a monolithic structure with actuators that can be combined with others to create “multi-limbed” soft devices. The design choices for the robot are the structure and fabrication - the soft material(s), the shape of the robot and fabrication technique, actuation - the type, number and placement of the actuators, and the friction manipulation mechanism. Because the robot is a continuum system, these design features are intricately coupled. Soft linear animals like caterpillars locomote by changing their body shape and manipulating friction at finite points using their passive gripping prolegs [29] (Figure 1). These animals are the design inspiration for the soft robot body and gripper-like friction manipulation mechanism which utilizes differential friction to facilitate locomotion.

**Structure design and fabrication.** The robot body is made from a deformable material with horizontal ribs (Figure 2). The ribs facilitate bending in the desired direction and cooling of the temperature-dependent actuators. The whole device is printed on a multi-material printer (Connex 500™) [30] using TangoPlus™ (Shore A Hardness) as the soft, rubber-like material and VeroClear™ (Shore D Harness) for the hard material. The robot body is 80 mm long and weighs between 3 to 3.6 gm (Figure 2).

**Actuation.** The robot is actuated using two shape memory alloy (SMA) coils [31] that are threaded through open channels inside the robot above the mid-line of the robot body resulting in concave shape bending when they are actuated (Figure 2). The location of SMA attachment points and the resulting overlap may be varied for different robots with the condition that each actuator can independently control the friction mechanism at each end of the robot. Each actuator is pre-stretched when it is installed and is activated by using current pulses that heat the SMA causing the coil to shorten. Elastic forces in the body materials restore the original actuator length when it is allowed to cool. Activation of a single SMA actuator is periodic where the strength of the actuation current pulse (S), proportional to the current supplied to the actuator.

Fig. 2: The top and side views of the soft robot. The body of the robot is made out of soft material. The 80mm long soft robot body is controlled using two overlapping SMA coils. The virtual grip variable friction mechanisms allow controlled manipulation of friction.

![Image](attachment:shape-memory-alloy-based-actuation-pattern.png)

**Fig. 3:** Shape memory alloy based actuation pattern for one and two actuators.

The SMA actuators are inconsistent over time, mainly because of the non-uniform transitions (due to cooling rate, etc.) of crystals between the austenite and martensite phases [32].
The variable friction mechanism consists of two materials (M₁ and M₂) which have different friction coefficients. The angle between the body tangent at the end and the surface horizontal is referred to as the contact angle \( \psi \). The coefficient of friction changes after the critical contact angle \( \psi^* \). The binary states 0, 1 directly relate to the material in contact i.e. friction.

Friction manipulation mechanism. Frictional force arises from the interaction of irregularities between surfaces in contact [19, 33] and depends on the material and its texture. The change of robot shape (bending) upon actuation changes the angle between the body tangent at the end of the beam-like robot body and the surface horizontal which is referred to as the contact angle \( \psi \). This is the basis of the shape dependent friction mechanism (Figure 4). The contact surface is made from two different materials M₁, M₂ with different coefficients of frictions. As the contact angle \( \psi \) changes about the critical contact angle \( \psi^* \) the friction changes from one value to the other. This two-material differential friction mechanism is similar to a biological gripper such as the caterpillar proleg that is on (very high friction) or off (zero friction). Hence, the friction mechanism is identified by binary states (S) such that

\[
S = \begin{cases} 
0 & \text{for } (\psi - \psi^*) < 0 \\
1 & \text{for } (\psi - \psi^*) \geq 0 
\end{cases} 
\]

(1)

This friction mechanism makes use of the different interactions exhibited by soft and hard materials on surfaces of varying roughness (Figure 5). When two hard materials are pressed together, friction is largely determined by the effective area of contact which itself depends on how well the surface irregularities interlock. This is a function of the size and match of asperities in the two materials (Figure 5a). However, during interactions between hard and soft surfaces the soft/flexible material has the ability to flow and conform to asperities of the harder material surface, thus, increasing friction (Figure 5b). In this case the friction depends far more on the applied load than it would for two hard surfaces [19]. Hence, in the present case for the same load applied, the soft material is stickier with higher coefficient of friction compared to the hard material, thus, providing differential friction. The mechanism works as follows - as the SMA coil is electrically actuated, the consequent bending of the robot results in change of the contact angle. When the contact angle \( \psi \) exceeds the critical contact angle \( \psi^* \), the contact material changes from M₁ to M₂. Upon deactivation (no current flow), the SMA coils cool and the intrinsic elasticity of the bent body results in straightening of the robot, equivalently, decrease in contact angle. Now, when the contact angle is less than the critical contact angle, the contact material changes to M₂. So, this gripper-like friction manipulation mechanism allows for the friction force acting on the robot to change with its shape. This design can be interpolated to multi-state, multi-material (with different friction coefficient) friction manipulation mechanisms.

C. Robot-environment interaction

The robot interacts with the environment via the discrete contact friction manipulation mechanisms. This interaction is complicated to analyze and model e.g. quasi-static analysis of this frictional interaction makes it dependent upon the coefficient of friction (material M₁, M₂) and the normal force at each friction mechanism. The normal force is coupled to changes in shape of the robot which depends on the placement, activation of the actuators. As a result, non-symmetric and symmetric bending of the robot creates different normal and frictional forces for contraction (Figure 6a) and relaxation (Figure 6b). However, the robot-environment interaction at finite contact points and discretization of the contact behavior (Equation 1) allows the robot behavior to be defined.

The robot behavior is defined as the states of the two friction mechanisms and is written as \( (S₁, S₂) \) where \( Sᵢ \) corresponds to state of the \( ᵢ \)th friction mechanism. Exhaustively, the four robot states in the present case are \( \{00, 01, 10, 11\} \). Discretization of the robot-environment interaction using these robot states is instrumental for the control system design.

III. SOFT ROBOT CONTROL

Control of soft material robots is typically performed by continuum modeling techniques [10, 11, 34–36] and finite element methods [37]. A particular challenge for these approaches in terrestrial locomotion is that interaction of the
robot with the environment is difficult to model and simulate. However, the discretization of finite point robot-environment interaction discussed in Section II-B, II-C facilitates development of a robot state-based control framework. This framework indirectly models the robot-environment interaction and helps in calculation of optimal control sequences for locomotion.

A. State transition and control framework

As discussed in Section II-C, the robot can exist in one of four states. The transition from one state to another results in linear displacement of the center of mass (termed as reward) - forward, backward or none that is discretized as +1, -1 or 0. The result of a single state to state transition is stored inside a state transition reward matrix \( T \in \mathbb{R}^{2 \times 2} \). The element \( T_{ij} \) represents the displacement for a transition from state \( \text{dec2bin}(i - 1) \) to \( \text{dec2bin}(j - 1) \) e.g. \( T_{13} \) represents the discretized displacement when the robot transitions from state \((00)\) to \((10)\). Rather than direct modeling of surface interactions, the transition matrix represents relative differences in friction, a critical aspect of locomotion. This framework is referred to as the model-free control framework. It is expected to have general applications with the following advantages

1) **Material and actuator independence.** The transition from one state to another is only dependent on the critical contact angle (\( \psi^* \)). The robot state can be measured using an angular feedback sensor (e.g. MEMS inertial sensor) without the need to model the actuator (SMA, motor-tendon, pneumatic, etc) or even the specifics of the body material (rubber, PDMS, TangoPlus\textsuperscript{TM}).

2) **Friction manipulation mechanism independence.** The framework is applicable to scenarios where the friction manipulation can be discretized into finite number of behaviors such as a gripper (zero, infinite friction) or a unidirectional roller. Furthermore, the number of discretized behaviors is not restricted to two but can be applied to friction mechanisms made of multiple materials (two or more critical contact angles).

3) **Simplification of control parameters.** Using this framework, the control parameters for \( N \) friction mechanisms decrease from \( 4^N - 1 \) to \( N \) (number of critical contact angles). For the robot presented here, the number of control parameters decreases from 7 (Figure 3) to 2. Furthermore, changes in the SMA actuation properties can be easily compensated using the discretization process.

4) **Adaptability to changing environment.** The state transition rewards result from the robot-environment interaction which provides a relatively straightforward mechanism to adapt to changing environments. The adaptability is expected to be achieved through a layer of intelligence that learns the state transition rewards as environment changes.

5) **Calculation of optimized control sequences.** State transition rewards represent the transition between two individual states. However, it is possible to calculate optimal control sequences by optimizing cost functions. This is discussed in Section III-B.

6) **Extendible to multiple limbs/actuators.** The framework is extendible to multi-limbs/actuators.

B. Control sequences and speed

A control sequence is defined as a sequence of state transitions \( S(t) \) for \( t = 1, 2, \ldots, N \). The resulting translation reward \( J_x \) for the given sequence is written as

\[
J_x (\{S(t)\}) = \sum_{t=1}^{N} T_{S(t-1),S(t)}
\]  

The calculation of optimal periodic control sequence \( S_x^* \) for maximum translation in \( +X \) direction can be calculated as

\[
S_x^* = \max_{S(t) \text{ s.t. } S(0)=S(N)} \{J_x\}
\]  

with the constraint \( N \leq l_{\text{max}} \) where \( l_{\text{max}} \) is the maximum length of the sequence. For the research experiment \( l_{\text{max}} = 4 \). Here it is important to note that the speed of the robot locomotion directly depends upon its ability to transition from one state to another which dictates the speed of implementation of the control sequences.

IV. Experiments

The model-free control framework was used in experiments to explore how soft robots with different friction arrangements affected the optimal locomotion sequences. The state transition matrix is unique to each robot as it corresponds to the unique robot-environment interaction and needs to be learned. This state transition matrix is critical for calculating the optimal control sequence (Equations 2, 3). For this initial study, the matrices are manually learned from visual feedback.

Using soft and hard materials in the variable friction mechanism allows two order-dependent designs referred to as \( D_1 \) (\( M_1 \) is soft, \( M_2 \) is hard) and \( D_2 \) (\( M_1 \) is hard, \( M_2 \) is soft). Consequently, three possible combinations are explored - two symmetric cases with \( D_1 \) at both ends (robot \( R_1 \)) and \( D_2 \) at both ends (robot \( R_2 \)). The third non-symmetric design has \( D_1 \) at one end and \( D_2 \) at the other end (robot \( R_3 \)). The Table I records the robot type and transition matrix associated with the corresponding robot where soft, hard materials are indicated by dark grey and pale yellow colors respectively. The calculation of optimal locomotion sequences in \( +X, -X \) directions using...
A small, lightweight (3-3.6gms), soft material modular robotic platform has been developed to explore new approaches of soft robot control. The robots are printed on a multi-material 3D printer making their manufacturing and assembly fast and cheap. Inspired by a biological example, the robot is a simple deformable body actuated by muscle-like SMA coils and interacting with the environment at finite discrete points. Instead of building a directly actuated mechanism for controlling grip, friction is manipulated using two materials with different properties. The robot alters its frictional interaction with the environment through changes in shape to produce locomotion.

Control is achieved by indirect modeling of the robot-environment interaction using the model-free control framework. Here, the friction interactions (gripper-like behavior) are discretized as binary states 0, 1. These binary states allow definition of four robot states and a state transition matrix. The individual robot state transition rewards are learned and stored in the transition matrix. Optimization allows the sequence of state transitions to be calculated to control robot locomotion. The transition matrix is expected to be helpful for robots maneuvering in unstructured and unpredictable environments as it does not depend on the robot dynamics. This matrix may be learned and repopulated using control feedback to tackle unanticipated environmental changes, thus, making the robot more robust. Another advantage of the state-transition matrix is that it avoids the need to model interactions with the surface. The objective of state-transition matrix is to avoid direct modeling of friction or grip. The state-based discretization allows the control strategy to compensate for inconsistent SMA actuators and simplifies translation of control schemes to non-SMA based soft robot actuators such as motor-tendon based robots. Furthermore, the presented framework is generic, simplifies control parameters, material and actuator independent and extendable to multiple limbs/actuators.

Experiments demonstrate how this framework can be applied. Three different types of robots generated control sequences that produced anteriograde and retrograde waves equivalent to those seen in soft moving animals [38]. The approach is also expected to apply to robots moving in changing conditions or when the robot itself undergoes a loss. This was illustrated by turning one of the actuators off and identifying two control sequences that produce forward locomotion. These experiments also showed that the contact angle $\psi$ (equivalently, state), is sufficient for controlling actuation instead of the actuation time ($T_{\text{active}}$).

These bio-inspired robots are simple but powerful platforms to explore new mechanisms of locomotion control in soft devices. They can be easily developed into more structurally complex and capable robots by adding additional beams (analogous to limbs) to produce shapes like the letters Y and X, or increasingly radial configurations such as a starfish. The control framework can also be expanded for planar locomotion in which the robot-environment interaction is a vector of both changes in position and orientation. These studies are underway to explore the advantages and limitations of using a model-free control approach for soft robots in complex environments.

| | Left | Right | Transition Matrix |
|---|---|---|---|
| $R_1$ | [Image] | [Image] | $\begin{bmatrix} 0 & -1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$ |
| $R_2$ | [Image] | [Image] | $\begin{bmatrix} 0 & 1 & -1 & 0 \\ -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$ |
| $R_3$ | [Image] | [Image] | $\begin{bmatrix} 0 & -1 & 1 & 1 \\ 1 & 0 & 0 & -1 \\ -1 & -1 & 0 & -1 \\ -1 & 1 & 0 & 0 \end{bmatrix}$ |

TABLE I: Transition matrices corresponding to the three combinations. The two hard, soft materials in the virtual grip friction mechanism are illustrated by dark grey and pale yellow colors respectively. The first two rows corresponds to identical friction mechanisms at both ends while the third row corresponds to non-symmetrical arrangement.

Equation 3 for the three robots resulted in two periodic control sequences - $C_{T1} = \{(00) \rightarrow (10) \rightarrow (01) \rightarrow (00)\}$ and $C_{T2} = \{(00) \rightarrow (01) \rightarrow (10) \rightarrow (00)\}$. These correspond to propagation of anteriograde wave and retrograde waves respectively. The transition matrices for symmetrical designs are transpositions of one-another - hence the similarity in locomotion sequences. With the same execution time for both four state control sequences, movement is identical in both locomotion sequences. With the same execution time for both four state control sequences, movement is identical in both locomotion sequences. With the same execution time for both four state control sequences, movement is identical in both locomotion sequences. With the same execution time for both four state control sequences, movement is identical in both locomotion sequences. With the same execution time for both four state control sequences, movement is identical in both locomotion sequences.

The objective of states-transition matrix is to avoid direct modeling of friction or grip. The state-based discretization allows the control strategy to compensate for inconsistent SMA actuators and simplifies translation of control schemes to non-SMA based soft robot actuators such as motor-tendon based robots. Furthermore, the presented framework is generic, simplifies control parameters, material and actuator independent and extendable to multiple limbs/actuators.

Loss of limb/actuation. This control scheme should be robust to changes in the physical structure such as limb-loss. To test this scenario, the $R_1$ robot was actuated using only one SMA (left/rear). Consequently, the robot cannot transition into state (01) or between (00) and (11) independently (only via state (10)). Thus, the state transition reward matrix for this robot is modified as follows

$$T_{l.o.a.} = \begin{bmatrix} (00) & (01) & (10) & (11) \\ (01) & 1 & 0 & 1 \\ (10) & 1 & 0 & 1 \\ (11) & 0 & 0 & 1 \end{bmatrix}$$

where the red strikeouts infer the forbidden state transitions. The optimization proceeds in the same way without anything extra being learned. For $l_{max} \leq 5$ the two control sequences for $+X$ translations are $C_{L1} = \{(00) \rightarrow (10) \rightarrow (11) \rightarrow (10) \rightarrow (00)\}$ and $C_{L2} = \{(10) \rightarrow (11) \rightarrow (10)\}$, both resulting in $+1$ resultant translation.

V. CONCLUSION

A small, lightweight (3-3.6gms), soft material modular robotic platform has been developed to explore new approaches of soft robot control. The robots are printed on a multi-material 3D printer making their manufacturing and assembly fast and cheap. Inspired by a biological example, the robot is a simple deformable body actuated by muscle-like SMA coils and interacting with the environment at finite discrete points. Instead of building a directly actuated mechanism for controlling grip, friction is manipulated using two materials with different properties. The robot alters its frictional interaction with the environment through changes in shape to produce locomotion.

Control is achieved by indirect modeling of the robot-environment interaction using the model-free control framework. Here, the friction interactions (gripper-like behavior) are discretized as binary states 0, 1. These binary states allow definition of four robot states and a state transition matrix. The individual robot state transition rewards are learned and stored in the transition matrix. Optimization allows the sequence of state transitions to be calculated to control robot locomotion. The transition matrix is expected to be helpful for robots maneuvering in unstructured and unpredictable environments as it does not depend on the robot dynamics. This matrix may be learned and repopulated using control feedback to tackle unanticipated environmental changes, thus, making the robot more robust. Another advantage of the state-transition matrix is that it avoids the need to model interactions with the surface. The objective of state-transition matrix is to avoid direct modeling of friction or grip. The state-based discretization allows the control strategy to compensate for inconsistent SMA actuators and simplifies translation of control schemes to non-SMA based soft robot actuators such as motor-tendon based robots. Furthermore, the presented framework is generic, simplifies control parameters, material and actuator independent and extendable to multiple limbs/actuators.
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