Redundancy in the Control of Robots with Highly Coupled Mechanical Structures

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***Abstract*— This paper investigates the hypothesis that robots based on highly coupled mechanical structures can give rise to redundancy in control. Highly coupled mechanical structures have the property that actuation at one location can translate into movement at multiple locations, and conversely, movement at one location can be caused by multiple actuators. Due to this property, multiple control strategies may exist for a single behavior. Tensegrity structures which have recently been shown to form the basis for successful locomotor robots [8], have highly coupled mechanical structures. Thus, as a case study, it was of interest to investigate whether these new tensegrity based robots could offer a high degree of redundancy of control. This was investigated on two robots, based on three and four strut tensegrity prisms. Control strategies for locomotion were evolved using a genetic algorithm in simulation, and the evolved behaviors were compared. It was found that multiple control strategies existed for forward locomotion in both structures, and that qualitatively similar behavior could be obtained with significantly different control strategies. This indicated that a considerable degree of redundancy could exist in the control of robots based on highly coupled mechanical structures.**

I. Introduction

The conventional design of locomotor robots has been based on a series of rigid links connected by prismatic or revolute joints, actuated using electric motors, pneumatic or hydraulic actuators. The majority of legged robots have been based on this design [5] [13] although in some robots, geared towards dynamic gait, the actuators have been supplemented with series elastic elements [11] or replaced with passive compliance [1][12]. In such a design, actuation at one degree of freedom may or may not effect the state of another degree of freedom. For example, bending one knee may not affect the hip joint angle of another leg in a quadruped robot.

In this work, however, the goal was to depart from this conventional design and explore the use of coupled mechanical structures for robots, in which the activation of one actuator could affect multiple locations. The aim was to to evaluate whether such a structure could give rise to higher redundancy in control, such that multiple actuation patterns could give rise to the same behavior.

Traditionally, the existance of multiple control strategies for a behavior has not been considered a criteria as controllers have been hand designed for a particular robot and task. However, with the advent of machine learning methods, controllers can be automatically designed for robots using gradient based search through the space of possible controllers. Such methods are likely to grow in importance for autonomous and remote operation, where it is necessary to adapt on-line to changes in task requirements, environment, and morphology (due to physical damage, for example). In this context, it is advantageous to have a space in which multiple control strategies exist, as it can greatly optimize the time required to acquire new behaviors. Thus, the design of robots which allow for redundancy in control is relevant.

In this study, it was investigated whether highly coupled mechanical structures can give rise to greater redundancy in control. Tensegrity structures were selected as the basis of the investigation as they are highly coupled; application of force at one location of the structure results in a global deformation. Tensegrity structures were first invented by Snelson in 1948 and formally patented by Buckminister Fuller in 1962 [2], who coined the word tensegrity as an abbreviation of *tensile integrity*. The general definition of a tensegrity structure is a structure that maintains a stable volume in space through the use of discontinuous compressive elements (struts) connected to a continuous network of tensile elements (cables) [10]. Tensegrity has been used in the design of bridges and geodesic domes [4], and in the design of lightweight space structures



Fig. 1. A Tensegrity Robot

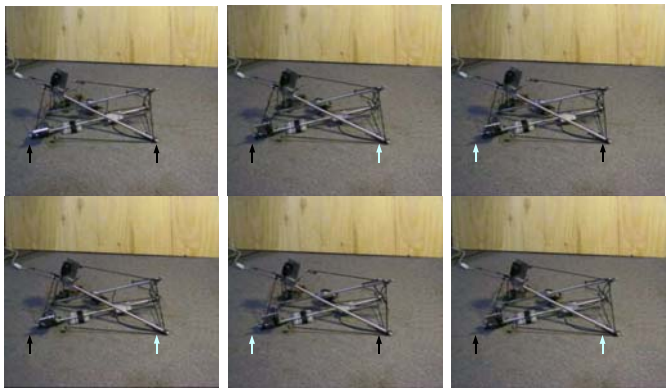


Fig. 2. Still frames extracted from video of robot walking. The robot walks by alternating forward movement in the two bottom struts. Arrows have been added to indicate the original location of the strut ends. The arrow is colored light to indicate which strut has just been moved.

such as deployable masts [3] and reflector antennas [16][6]. However, it has rarely been studied in the context of robotics, except by Aldrich *et al* [14] who investigated the control of a tensegrity based robotic manipulator. In general, such highly coupled structures are avoided in robotics as they lead to complicated kinematics and dynamics, that are challenging to analyse and control. Thus, the conventional design of robots is usually based on serial linkages.

However, the fact that actuation at one location in a tensegrity structure can lead to motion in various others, suggests that there may be a high degree of redundancy in the ability to produce behavior using various actuation patterns. In order to explore this potential, the control of tensegrity robots was further investigated. In preliminary work a tensegrity robot was designed based on a three strut tensegrity prism (Fig. 1), and controlled to walk using a pre-programmed sequence of states changes in its actuators (Fig. 2). The results validated the concept of a tensegrity robot for locomotion [8].

In this paper, redundancy of control for locomotion was investigated in simulation for two robots, TR-3 and TR-4, based on three and four strut tensegrity prisms. Periodic gait controllers were evolved for the robots using a genetic algorithm, and the evolved control strategies were compared. The results showed that multiple control strategies could give rise to similar performance in terms of both speed and gait pattern, indicating a certain measure of redundancy of control in the system.

II. Tensegrity Structures

The tensegrity structures were implemented in the *Open Dynamics Engine* (ODE) simulation environment, which provided physics based simulation of rigid body motion. It included implementation of the frictional characteristics of ground surfaces, gravity, and the dynamics of multi-link rigid bodies composed of various types of joints.

The struts of the tensegrity structures were implemented as rigid cylindrical bodies. The outer surfaces of the struts had elastic contact properties such that when in contact with another surface they generated forces which resisted penetration. The cables, in contrast, were implemented as virtual objects whic were massless, volumeless, and did not have any contact characteristics. Each cable was represented by a collinear pair of forces, one of which is applied at the end of each strut to which the cable is attached. The magnitude of the force F was based on a spring-damper model:

$$F = \frac{k}{l_o}(l - l_o) - c\dot{l} \tag{1}$$

where l was the current distance between the relevant strut endpoints, l_o the spring rest length, k the spring coefficient and c the damping coefficient. The forces were applied along the instantaneous location of the line joining the end points of the two struts to which the cable was attached.

Figures 3 and 4 show the morphology of the TR-3 and TR-4 robots, and Tables 1 and 2 show the values of the parameters used in the implementation of these robots respectively.

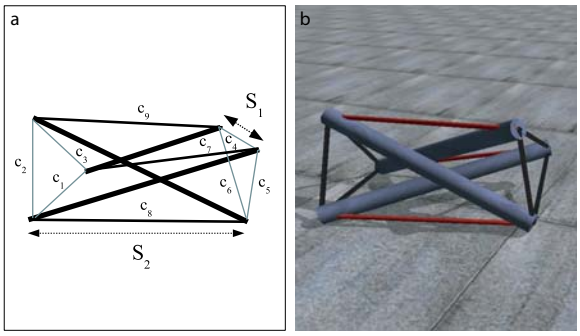


Fig. 3. a) Schematic of the 3-prism tensegrity structure. The thick black lines indicate the struts. The thin grey lines indicate the cables at the two ends of the prism. These are all of length S_1. The thin black lines indicate the transverse cables connecting the two sides of the prism. These are of length S_2. b) The robot TR-3, based on the 3-prism tensegrity structure, in simulation.

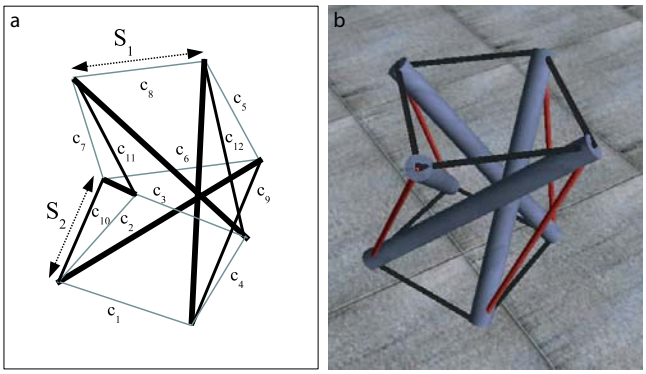


Fig. 4. a) Schematic of the 4-prism tensegrity structure. The thick black lines indicate the struts. The thin grey lines indicate the cables at the two ends of the prism. These are all of length S_1. The thin black lines indicate the transverse cables connecting the two sides of the prism. These are of length S_2. b) The robot TR-4, based on the 4-prism tensegrity structure, in simulation.

TABLE I

Values of parameters for the TR-3 robot

strut length	1.01 m
cable spring constant k	0.70 N/m
cable damping constant c	10.00 Ns/m
cable rest length S_1^o (short)	0.35 m
cable rest length S_2^o (long)	0.44 m
equilibrium cable length S_1	0.44 m
equilibrium cable length S_2	0.88 m

TABLE II

Values of parameters for the TR-4 robot

strut length	1.00 m
cable spring constant k	0.70 N/m
cable damping constant c	10.00 Ns/m
cable rest length S_1^o (short)	0.24 m
cable rest length S_2^o (long)	0.23 m
equilibrium cable length S_1	0.51 m
equilibrium cable length S_2	0.80 m

A. Actuation

Three methods of actuation are possible in a tensegrity structure: strut-collocated, cable-collocated and non-collocated actuation. In strut-collocated actuation, the actuators are responsible for altering the strut lengths. In cable-collocated actuation, the structure is modified by changing the effective rest length of the cables. In non-collocated actuation, actuation is applied between two struts, two cables, or a strut and a cable.

Cable-collocated actuation was selected for both the TR-3 and TR-4 robots. On the TR-3 and TR-4 robots, the cables were located on the longitudinal cables of the prisms as indicated in Figures 3 and 4 by the black cables (c_7-c_9 in TR-3, and c_9-c_{12} in TR-4). The actuators applied force on the structure by effecting a change in the rest length of these cables. For the TR-3, the maximum change in the cable length was 0.10m and for the TR-4 robot, the maximum change was 0.06m. The control of the robot was accomplished by periodically changing the rest lengths of these cables between the maximum and minimum values. In simulation, this change was considered to be instantaneous.

III. Controller Design Using Genetic Algorithm

Each actuator was contracted once during each gait cycle. The phase of the gait cycle at which each actuator was activated, the duration of the contraction, and its amplitude were determined by a genetic algorithm independently for each actuator. The period of the gait was also determined by the genetic algorithm.

Thus, the relevant parameters in the control were:

λ period of the gait cycle
α_i amplitude of actuation for each cable
ϕ_i phase of onset of actuation for each cable
δ_i duration of actuation for each cable
$l^r_{c_i}$ current rest length of each cable
$l^o_{c_i}$ original rest length of each cable
t^o_i time of onset in each cycle
t time

The controller had the following algorithmic form:

In each time step, for each cable c_i:

$$\textit{if } t \bmod \lambda = \phi_i, \textit{ set } t_i^o = t$$

$$l^r_{c_i} = \begin{cases} l^o_{c_i} - \alpha_i l^o_{c_i} & : \quad t_i^o < t < t_i^o + \delta_i \\ l^o_{c_i} & : \quad t > t_i^o + \delta_i \end{cases}$$

According to this, actuation of a cable was initiated when t was at the phase of onset specified by the parameter ϕ_i. At this point the parameter t_i^o was initialized to the value of t. Subsequently, the cable was activated for δ_i time steps, and then deactivated for the rest of the gait cyle.

A genetic algorithm [7] was used to search the space of possible controllers. Each agent in the population had a genome string with floating point values between 0 and 1. The first value in the string, p, encoded the period of the gait cycle. The rest of the genome string was composed of triples $[a_i, o_i, d_i]$ encoding the amplitude, phase and duration for each cable. The parameters λ, α_i, ϕ_i and δ_i were determined from these values as follows:

$$\lambda = \lambda_{min} + \lfloor p(\lambda_{max} - \lambda_{min}) \rfloor$$
$$\alpha_i = \lfloor a_i \alpha_{max} \rfloor, \quad \phi_i = \lfloor o_i \lambda \rfloor, \quad , \delta_i = \lfloor d_i \lambda \rfloor$$

where λ_{max} = 500, λ_{min} = 200, α_{max} = 0.10.

A fixed length genetic algorithm was used to evolve the controllers. Each run of the genetic algorithm was conducted for 200 generations, using a population size of 200. At the end of each generation, the 100 most fit genomes were preserved; the others were deleted. Tournament selection with a tournament size of three, was employed to probabilistically select genotypes from among those remaining for mutation and crossover. 25 pairwise one-point crossings produced 50 new genotypes: the remaining 50 new genotypes were mutated copies of genotypes from the previous generation. The mutation rate was set to generate an average of n mutations for each new genome created, where n was defined as a function of the genome length g_l, as $n = g_l/11$. Mutation involved the replacement of a single value with a new random value. The floating-point values were rounded to two decimal places and thus ranged between 0.00 and 1.00. For the TR-3 robot the genome had 10 values and for the TR-4 robot, 13 values. The first value represented the period of the gait cycle, and the rest of the genome consisted of triples representiing phase, duration and amplitude of actuation for the three actuated cables.

During evolution each individual was evaluated for $10,000$ time steps of the dynamics simulation, where each time

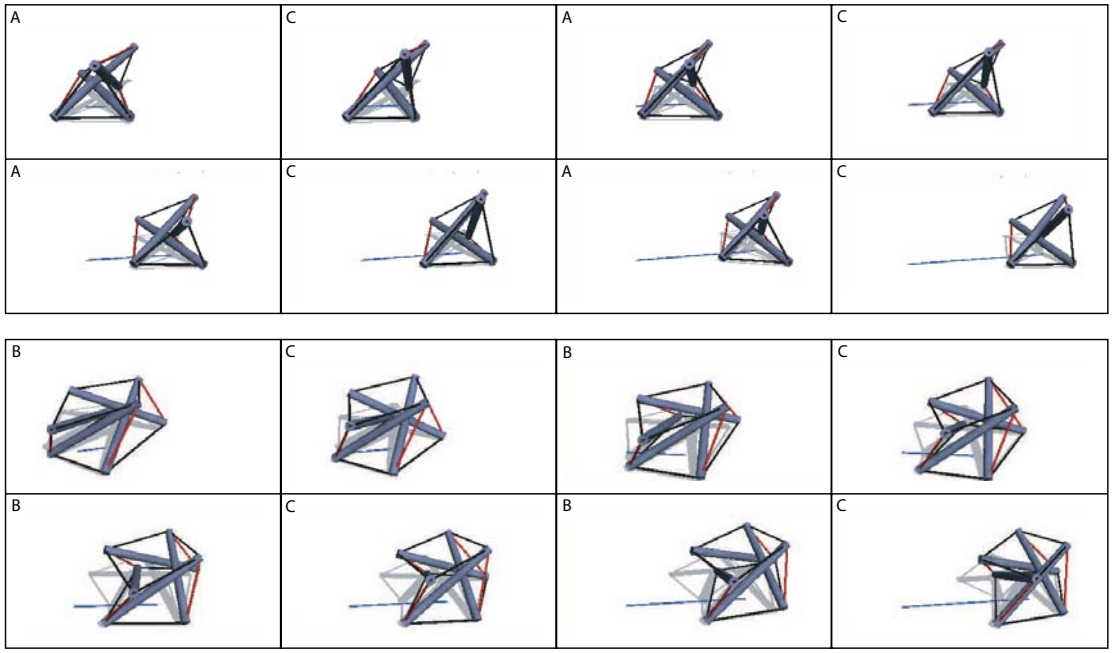


Fig. 5. Still frames extracted from video of TR-3 and TR-4 robot locomotion. The trace on the ground indicates the line between the original and current position of the robot.

step corresponded to 0.001s. The initial condition for each individual at the first time step was at position [0, 0] in the x-y plane. The fitness of the individual was determined at the end of the evaluation period, and was considered to be the distance travelled in the y-direction with respect to the origin during 10s.

IV. Results

Ten experiments were performed with the TR-3, and sixteen with the TR-4. The results indicated successful production of motion in all the experiments with varying speeds and gait patterns. For the TR-3, the best distance acheived at the end of evolution ranged from 1.6m to 4.5m and for the TR-4, the distance ranged from 2.9m to 4.9m. Various gait patterns were obtained in the experiments. Some agents achieved slow and static gait patterns, while others achieved fast and dynamic gait patterns similar to hopping or bounding. Still frames extracted from videos of the robots during dynamic locomotion are shown in Fig. 5.

Redundancy of control implies that multiple control strategies can lead to similar performance in terms of speed or gait pattern. To investigate this, for the ten experiments with the TR-3 and sixteen experiments with the TR-4, the difference in best fitness achieved at the end of the evolutionary run, was plotted with respect to the average difference in actuation pattern as specified by the genome values (Fig. 6). In a situation where there is only one way to achieve a certain level of performance, the difference in fitness is usually correlated with the difference in genome values. This means that when two agents have very similar fitness, they also have very similar genome values. However, in contrast to this situation, the scatter plot in Fig. 6 shows that in this case, very small differences in fitness can also result from large differences in genotype.

The points which were particularly noteworthy in the two plots were those in which the difference in fitness was less than 0.25, while the average difference in genome value was greater than 0.4. These are circled. For these points, although all the parameters including period, amplitude, phase and the duration of actuation for all the actuators differed on average by more than 40%, the performance in terms of speed of forward motion was very similar. This indicated that a certain measure of redundancy existed in the system.

In order to determine whether this redundancy could occur at all speeds, or whether there were particular regions of the space where the redundancy occured, the fitnesses of the pairs of agents that gave rise to the circled points in Fig. 6 were shown above them. For the TR-3, although the fitnesses ranged between 1.6m and 4.5m, all the fitnesses which gave rise to the circled points fell in a narrow region between 2.89 and 3.16. This indicates that for the TR-3 there may be particular speeds at which redundant control strategies exist. For the TR-4, the fitnesses were more widely spread in a range between 3.17m and 4.89m, indicating that multiple control strategies existed at multiple speeds.

However, similar performance in terms of fitness did not indicate that the behavior achieved was similar. In order to investigate redundancy of actuation, where different actuation patterns can lead to similar behavior, the behavior of the agents in some of the pairs were compared by plotting the cable forces of the actuated cables and the ground contact data for 1000ms. These are shown in Figures 7-9 for the TR-3 and Figures 10-

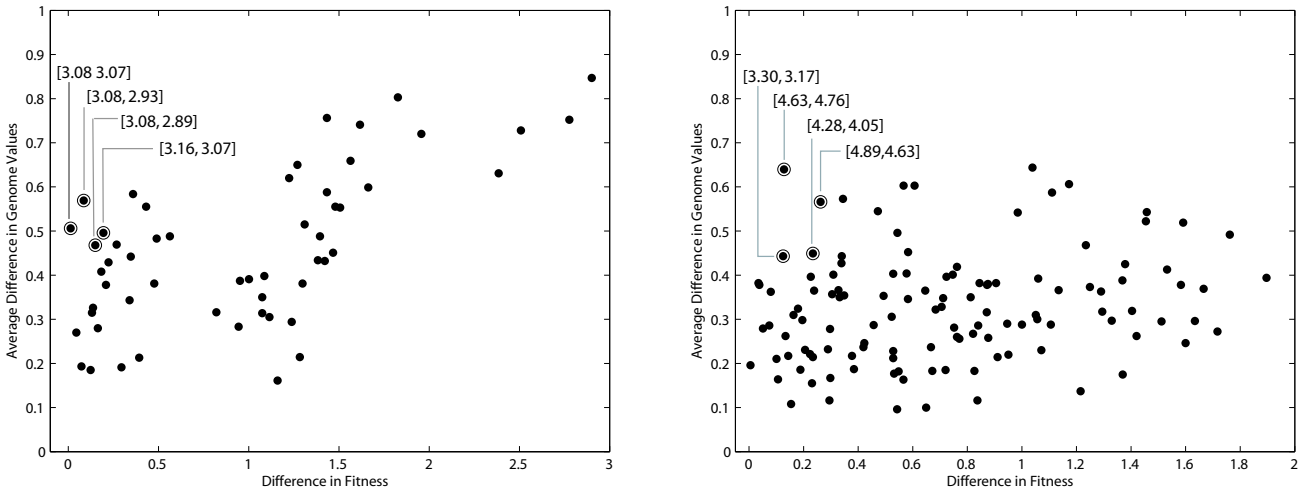


Fig. 6. Plot of difference in fitness versus difference in actuation pattern (specified by the genome values) for the best agents in the experiments. The trials in which there was a low difference in fitness value but a high difference in the genotype are circled. The fitness values of the pairs of agents that resulted in these data points are given above. (a) Results from best agents of the 10 experiments with the TR-3. (b) Results from the best agents of the 16 experiments with TR-4.

13 for the TR-4. In the graphs of cable forces, a sharp increase indicated activation of the actuator which caused a contraction of the cable, and a sharp decrease indicated deactivation of the actuator. Smoother changes were caused by the coupling effects due to other actuators. In the graphs of foot contact data, the dark line indicated that a foot was in contact with the ground while its absence indicated that the foot was in the air. The endpoint of each strut that was in a position to contact the ground was considered a foot. In Fig. 7, it can be seen that the pattern of actuation between the two agents is qualitatively different, as well the emergent pattern of foot contacts. The first agent lifts and places each of its feet for short durations while the second drags one of its feet for long periods. In Fig. 8, the pattern of actuation and the emergent gait are once again both qualitatively different. In Fig. 9 however, the pattern of actuation is different for the top two cables, but the emergent gait pattern is qualitatively similar.

For the TR-4, in Fig. 10 it can be seen that the patterns of actuation are qualitatively different, but the gait patterns achieved are similar in that they both have flight phases in which all four feet leave the ground at the same time, although the timing of when the the struts leave and touch the ground is slightly different. In the first case, some struts leave before others, while in the second case they are more simultaneous. In Fig. 11 the pattern of actuations clearly differ as the fourth cable is not used in the first case. The gait pattern is however has the same overall structure, differing slightly in the duration of foot contact. In Fig. 12 a similar effect is observed, in which qualitatively different patterns of actuation give rise to a similar gait, differing only in the ground contact duration of one foot.

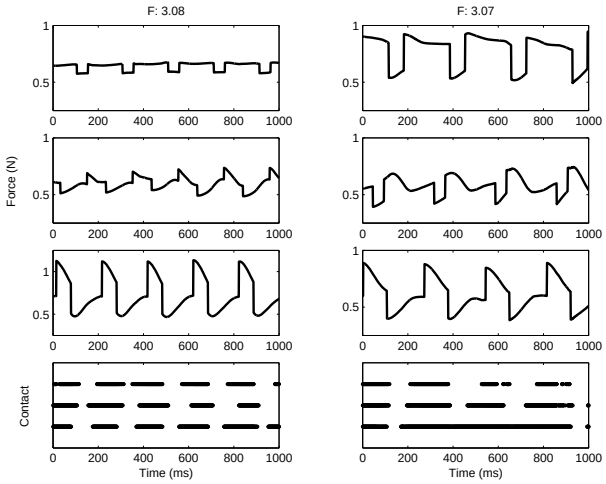


Fig. 7. Comparison between the results of two experiments with the TR-3 robot, resulting in similar fitnesses of 3.08 and 3.07 with highly different genotypes.

V. Discussion

In the experiments which generated the results shown in Figures 7-12, very similar performance in terms of speed and gait pattern was achieved with very different actuation patterns. The results demonstrate that multiple control strategies for locomotion can exist in these structures and indicate that a considerable degree of redundancy of control exists in such highly coupled mechanical structures. This can lead to the benefit that if an actuator being utilised in locomotion is damaged, another set of actuators can potentially be found to compensate for this, and to continue to perform the same behavior. Furthermore, machine learning methods could exploit such redundancy to more easily achieve effective gait patterns.

However, while these results indicate a positive relationship between mechanical coupling and redundancy of control, they do not negate the possibility that other kinds of structures could also demonstrate this feature. In fact, the use of coupled

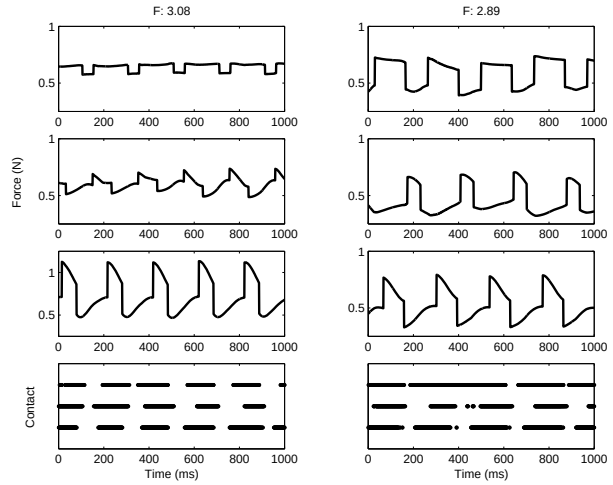


Fig. 8. Comparison between the results of two experiments with the TR-3 robot, resulting in similar fitnesses of 3.08 and 2.89 with highly different genotypes.

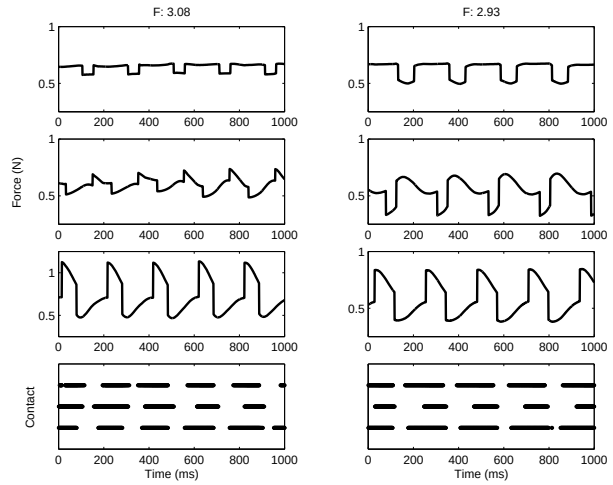


Fig. 9. Comparison between the results of two experiments with the TR-3 robot, resulting in similar fitnesses of 3.08 and 2.93 with highly different genotypes.

dynamics to achieve redundancy in control is a general problem which currently falls in a challenging domain of robotics. Although robotics has made great advances to date in the precision control of mechanical structures, a noticeable gap in the field is a corresponding understanding of the control of mechanical structures utilizing passively coupled dynamics. While passive dynamics have been broached in the context of legged locomotion, there are few analytical methods for the design of controllers utilizing passively coupled dynamics for a given task.

In a system with coupled dynamics, it is clear that when multiple degrees of freedom are effected by the same actuator, then they cannot be independently controlled. However, for walking it has been shown that not all the joints require independent control. In the swing phase of walking, the passive movement of the knee as a result of the hip joint is sufficient to satisfy the task requirements. This may well be the case for numerous other tasks. For example, it is known that when throwing a ball, the distal joints of the arm are allowed to swing passively in response to the motion of the proximal joints. Nonetheless, athletes can be trained to throw a ball very accurately to a target location. Thus, nature demonstrates that passive dynamics do not detract from the ability for precision movements.

Yet, in robotics, there are no methods to address the inclu-

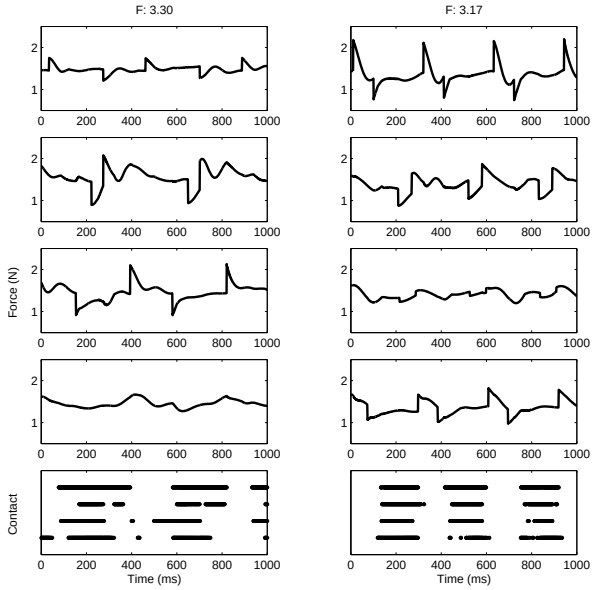


Fig. 10. Comparison between the results of two experiments with the TR-4 robot, resulting in similar fitnesses of 3.30 and 3.17 with highly different genotypes.

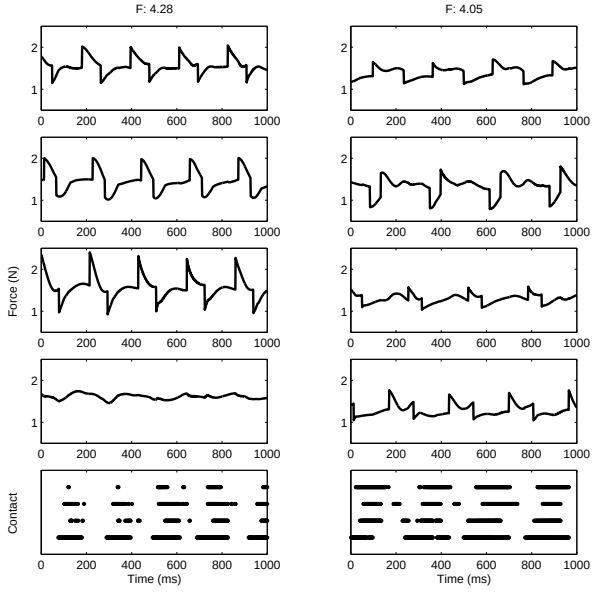


Fig. 11. Comparison between the results of two experiments with the TR-4 robot, resulting in similar fitnesses of 4.28 and 4.05 with highly different genotypes.

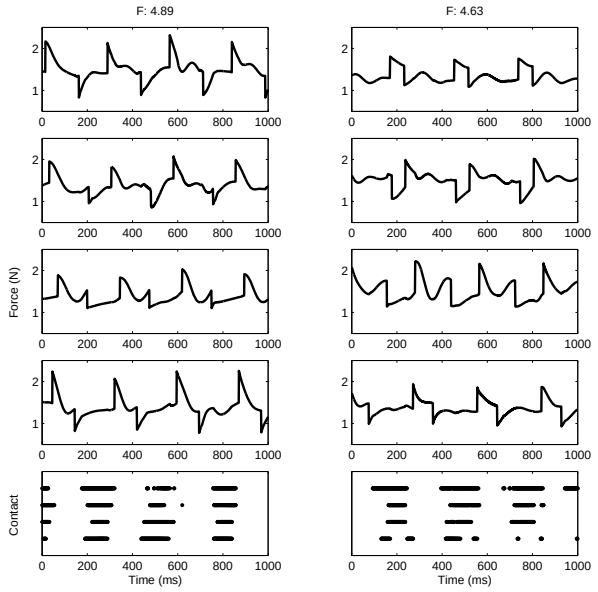


Fig. 12. Comparison between the results of two experiments with the TR-4 robot, resulting in similar fitnesses of 4.89 and 4.63 with highly different genotypes.

sion of passively coupled dynamics in control. For example, given a particular robot morphology and a particular task, there are no analytical methods to determine which degrees of freedom should be actively controlled, and which should be kept passive. This question can only be answered when there are methods to describe the coupled dynamics in the system and derive which degrees of freedom can be effectively controlled by a given set of control inputs.

Another interesting question is the relationship between morphology and coupling in mechanical structures. In both traditional robotic structures and tensegrity structures, movement at one location may or may not give rise to movement at another location depending on the specific shape of the structure. Currently, there is no general theory about how to design the shape of a mechanical structure to influence the degree and type of mechanical coupling it generates. While this work investigates this relationship in general for a category of structures, the more specific issue of how to design a structure to meet specific design requirements is unsolved. The development of methods to address these issues will provide challenging directions for future work.

VI. Conclusion

This paper investigated the redundancy of control in robots with highly coupled mechanical structures. Two highly coupled robot morphologies were designed based on tensegrity structures. The control of these robots for forward locomotion was performed in simulation using evolutionary optimization. It was found that 1) multiple control strategies existed for forward locomotion 2) similar performance in terms of speed could be obtained using qualitatively different control strategies 3) similar gait patterns could be obtained using different control strategies. The results indicated that highly coupled mechanical structures could give rise to considerable redundancy in control, which could enable greater versatility as observed in biological motor control.

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