

SkySweeper: A Low DOF, Dynamic High Wire Robot

Nicholas Morozovsky, Thomas Bewley

Abstract—SkySweeper is a mobile robot designed to operate in an environment of cables, wires, power lines, ropes, et cetera. The robot is comprised of two links pivotally connected at one end; a series elastic actuator at this “elbow” joint can actuate relative rotation between the two links. At the opposite end of each link is an actuated three-position clamp. The clamp can either be open, partially closed, such that the clamp can roll (translate) along the cable, or fully closed, such that the clamp can only pivot on the cable. By actuating the elbow joint and cleverly choosing the positions of the clamps, the robot can locomote on the cable in a number of different ways. The particular method of locomotion can be chosen to minimize energy consumption, maximize speed, or traverse an obstacle (e.g. a support from which the cable is suspended). SkySweeper has the potential to locomote in a more energy efficient manner than existing cable-locomoting robots. It also operates with a minimal number of actuators, which reduces cost significantly. Potential applications include power and communication line inspection, suspension bridge inspection and construction, as well as entertainment. Data from a prototype, consisting largely of 3D-printed and off-the-shelf parts, are compared to dynamic simulation results.

I. INTRODUCTION

Power lines, communication lines, hanging pipe, taut rope, and the like present an interesting environment for robotic systems to traverse. High wires, such as power lines (which may also be live at high voltage), are a dangerous environment in which using robots can improve human safety. Repetitive tasks such as inspection and monitoring naturally lend themselves to automation. Application areas in this type of environment include power line inspection and maintenance, communication line inspection, maintenance, and surveillance, suspension bridge inspection, maintenance, and construction, as well as entertainment and toys.

We begin by reviewing existing robots designed to locomote on cables. The application of power line inspection has been the largest motivator of cable-locomoting robotics research. An extensive survey paper was published in 2009 [1], which we encourage the reader to review. A few key examples are discussed here. Expliner is from the Japanese company HiBot which is closely affiliated with the Tokyo Institute of Technology. It can roll on one or two cables and circumvent multiple types of obstacles by shifting its center of mass and lifting one of two pulley arms, lowering it on the other side of the obstacle, shifting its center of mass under the second arm, and lifting the first arm [2]. LineScout was developed at Hydro-Québec IREQ directly for field use, it has a sliding mechanism with a redundant pair of clamps that

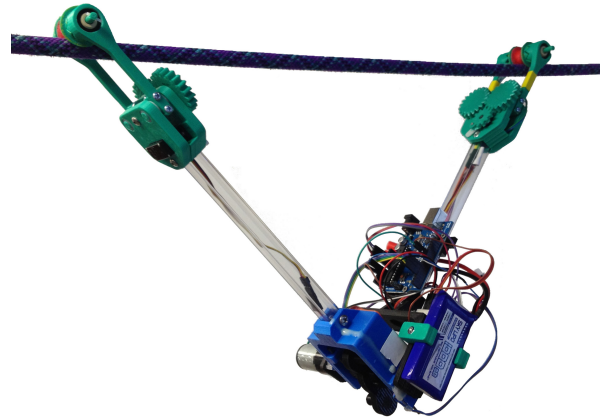


Fig. 1: SkySweeper prototype.

are only used for overcoming obstacles [3]. The dual-arm robot presented in [4] has three linear actuators, one in each arm and one in the chassis. Rotary actuators and powered clamps allow the robot to release one arm and pivot around obstacles as large as the robot. Cable Crawler, developed by Bühringer et al. at ETH Zürich, has large enough vertical and horizontal rollers to be able to passively roll over certain types of obstacles [5].

All the above mentioned robots perform quasi-static maneuvers with many degrees of freedom and many actuators. The systems are necessarily large, complex, and expensive. This leaves the field open to be disrupted with a mechanically simple design with few degrees of freedom, but agile, dynamic maneuvers.

In this paper, we present a novel new design for a cable-locomoting robot, which has few actuators, but multiple modes of locomotion for achieving different objectives. We first discuss the mechanical architecture of the robot and some of the maneuvers it can perform. Next we develop dynamic equations of motion that describe the behavior of the system under different configurations of the clamps. Third, we outline the controller as a finite state machine to implement the different maneuvers. Next we present the prototype that was constructed and compare its performance to the simulation results. We conclude with a summary and suggest future work for this system.

II. ARCHITECTURE & MANEUVERS

SkySweeper is symmetrically comprised of two links of equal length which are pivotally connected with a rotary series elastic actuator (SEA) at one end [6]. The SEA consists

Both authors are affiliated with the Coordinated Robotics Lab, University of California San Diego, La Jolla, CA 92093-0411 USA; e-mail: nmorozov@ucsd.edu, bewley@ucsd.edu

of a motor and a torsion spring connected in series. The motor housing is connected to the first link, the motor shaft is connected to one end of the spring, and the other end of the spring is connected to the second link. The motor exerts equal and opposite torques on the first link and the SEA shaft. The spring exerts equal and opposite torques on the SEA shaft and second link. At the opposite end of each link is an actuated clamp which can hold on to a cable. The clamp can be in one of three positions, as illustrated in Fig. 2:

- 1) Open, in which the clamp is completely open;
- 2) Rolling, in which the clamp is partially closed and may passively roll along the cable;
- 3) Pivoting, in which the clamp is fully closed and may only pivot on the cable.

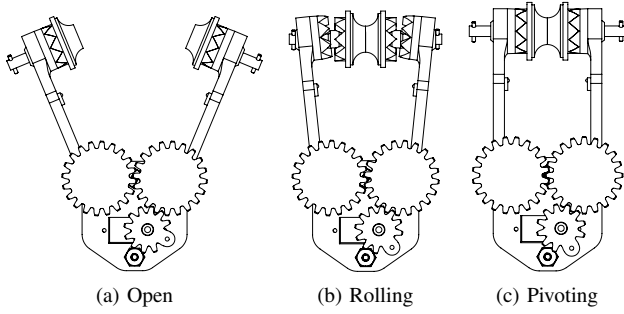


Fig. 2: Different clamp positions.

With two three-position clamps, there are a total of nine possible configurations. A sensor in each clamp detects when a cable is within grasp of the clamp. The SEA in the joint allows the robot to store extra potential energy before commencing a dynamic maneuver. By appropriately combining the actuation of the elbow SEA and the clamps, several modes of locomotion are possible.

A. Inchworm

In this maneuver, the robot has both clamps on the cable, one in pivoting position and the other in rolling position. The SEA is first actuated to increase the angle between the two links, then the positions of the clamps are alternated, the direction of the SEA is reversed to close the angle between the two links, and the clamp positions alternate again. The entire procedure is repeated which creates a successive “inchworm”-like motion to traverse the cable. This sequence of motions can be performed slowly (quasi-statically) for precise position control or quickly (dynamically with the SEA) to move faster.

B. Swing & Roll

The robot begins with both clamps on the cable, the motor in the SEA is allowed to spin idly. The first clamp is in the pivoting position and then the second clamp opens, causing the second link to pivot and fall away from the cable. As the center of mass rotates under the first clamp, the first clamp switches to the rolling position and the momentum from the swinging second link causes the robot to roll along the cable. If the first clamp were in rolling position the

entire time, there would be zero net horizontal displacement. This maneuver requires nearly zero control effort (just the small amount of energy required to actuate the clamps) and instead converts some of the gravitational potential energy into translational kinetic energy. Rolling resistance limits how far the robot will roll before coming to a stop. If the cable has a downward slope sufficient to overcome the rolling resistance, the robot will continue to roll. This maneuver allows efficient locomotion on horizontal and downward sloping cables.

C. Swing-Up

After the robot performs the previous maneuver, it comes to a rest with only the first clamp on the cable and both links hanging down vertically. In order to perform the inchworm maneuver, it is necessary to swing the second link up to grasp the cable. The swing-up maneuver starts with the first clamp in pivoting position on the cable and the second clamp open hanging down. A sinusoidal input is sent to the motor and the robot pivots and swings until the second clamp can grasp the cable. The frequency and magnitude of the sinusoid are chosen based on the physical parameters of the system.

D. Backflip

Instead of rolling along the cable, as in the inchworm and swing & roll maneuvers, the robot may also move along the cable by flipping end-over-end. The robot starts with both clamps on the cable in the pivoting position. In this configuration, all degrees of freedom of the robot are constrained, except for the spring in the SEA. The motor is driven to preload the spring and then the second clamp is opened. The force of the SEA and gravity cause the second link to rapidly pivot away from the cable. The motor continues (with less power) to rotate the second link relative to the first as the entire robot pivots about the first clamp until the second clamp grasps the cable. The spring is then preloaded in the opposite direction and the first clamp opens. The entire robot pivots about the second clamp in a similar manner as before until the first clamp can grasp the cable. This sequence of motions can be repeated for successive flips. An important advantage of this maneuver is that overhead obstacles, such as supports from which the cable hangs, may be bypassed.

All of the aforementioned maneuvers happen in the plane of the robot. The clamps constrain the robot from twisting out of plane. In an application environment, high winds could make some of the maneuvers (swing-up, backflip) untenable. Existing cable-locomoting robots are also susceptible to high winds. Due to the symmetry of the links and clamps, all maneuvers can be performed to move in either direction.

III. DYNAMICS

We simplify the model to three bodies in two dimensions. The generalized coordinates are defined in Fig. 3, where θ and α are the angles of the first and second links, respectively, from vertical, γ is the rotation angle of the SEA shaft from vertical, and x, y is the position of the clamping

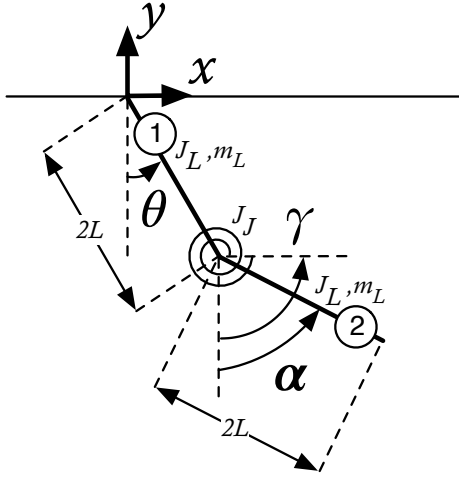


Fig. 3: Generalized Coordinates of SkySweeper.

end of the first link. The SEA spring deflection is then given by $\alpha - \gamma$ and the link separation angle is $\theta + \pi - \alpha$. The mass is assumed to be distributed uniformly along both links, each with length $2L$ and mass m_L , the SEA shaft has rotational inertia J_J , but negligible mass compared to each link. In this model, the cable is assumed to be horizontal and rigid.

The kinetic energies of the first link, joint, and second link are given respectively by:

$$\begin{aligned} T_1 &= \frac{1}{2} \left\{ m_L [(\dot{x} + L\dot{\theta} \cos \theta)^2 + (\dot{y} + L\dot{\theta} \sin \theta)^2] + J_L \dot{\theta}^2 \right\}, \\ T_J &= \frac{1}{2} \left\{ J_J \dot{\gamma}^2 \right\}, \\ T_2 &= \frac{1}{2} \left\{ m_L [(\dot{x} + 2L\dot{\theta} \cos \theta + L\dot{\alpha} \cos \alpha)^2 \right. \\ &\quad \left. + (\dot{y} + 2L\dot{\theta} \sin \theta + L\dot{\alpha} \sin \alpha)^2] + J_L \dot{\alpha}^2 \right\}. \end{aligned}$$

The spring and gravitational potential energy is given by:

$$V = \frac{1}{2} k(\alpha - \gamma)^2 + m_L g[2y - L(3 \cos \theta + \cos \alpha)].$$

We define q , the vector of n generalized coordinates, as

$$q = (x \ y \ \theta \ \gamma \ \alpha)^T.$$

The Lagrangian can be written as $\mathcal{L} = T_1 + T_J + T_2 - V$. By solving the Euler-Lagrange equations, we can write the equations of motion in the form

$$M(q)\ddot{q} + F(q, \dot{q}) = B\tau, \quad (1)$$

The (positive definite) mass matrix, $M(q)$, is given by:

$$\begin{aligned} M_{1,1}(q) &= 2m_L & M_{2,5}(q) &= m_L L \sin \alpha \\ M_{1,2}(q) &= 0 & M_{3,3}(q) &= 5m_L L^2 + J_L \\ M_{1,3}(q) &= 3m_L L \cos \theta & M_{3,4}(q) &= 0 \\ M_{1,4}(q) &= 0 & M_{3,5}(q) &= 2m_L L^2 \cos(\alpha - \theta) \\ M_{1,5}(q) &= m_L L \cos \alpha & M_{4,4}(q) &= J_J \\ M_{2,2}(q) &= 2m_L & M_{4,5}(q) &= 0 \\ M_{2,3}(q) &= 3m_L L \sin \theta & M_{5,5}(q) &= m_L L^2 + J_L \\ M_{2,4}(q) &= 0 \end{aligned}$$

and the vector $F(q, \dot{q})$ is given by:

$$F(q, \dot{q}) = \begin{pmatrix} -m_L L[3\dot{\theta}^2 \sin \theta + \dot{\alpha}^2 \sin \alpha] \\ m_L[L(3\dot{\theta}^2 \cos \theta + \dot{\alpha}^2 \cos \alpha) + 2g] \\ m_L L[3g \sin \theta - 2L\dot{\alpha}^2 \sin(\alpha - \theta)] \\ -k(\alpha - \gamma) \\ m_L L[2L\dot{\theta}^2 \sin(\alpha - \theta) + g \sin \alpha] + k(\alpha - \gamma) \end{pmatrix}.$$

The vector B maps τ , the control input torque for the motor in the elbow SEA, to the generalized coordinates:

$$B = \begin{pmatrix} 0 & 0 & -1 & 1 & 0 \end{pmatrix}^T.$$

Depending on the positions of the clamps, there may be holonomic and/or non-holonomic constraints on the system. We use the method of undetermined Lagrange multipliers, similarly to [7] and [8], to apply both holonomic and non-holonomic constraints. We first write the constraints in Pfaffian form: $A(q)\dot{q} = 0$ and append (1) with the inner product of the constraint matrix $A(q)$ with the Lagrange multiplier λ :

$$M(q)\ddot{q} + F(q, \dot{q}) = B\tau + A(q)^T \lambda. \quad (2)$$

Then we solve for $S(q)$, the orthonormal basis for the null space of $A(q)$. Given that $\dot{q}$ is in this space, we define the reduced coordinate vector ν accordingly as

$$\dot{q} = S(q)\nu. \quad (3)$$

Premultiplying by $S(q)^T$ and using (3), we can rewrite (2):

$$S(q)^T M(q) S(q) \dot{\nu} + S(q)^T F(q, \dot{q}) = S(q)^T B \tau. \quad (4)$$

The acceleration of the full coordinate vector, $\ddot{q}$, can be recovered using (3) and its time derivative.

The choice of $S(q)$ depends on the positions of the two clamps. If both clamps are open, there are no constraints on the system (and the robot will simply fall): $A_{OO}(q) = ()$ and $S_{OO}(q) = I_{5 \times 5}$. If clamp one is in rolling position and clamp two is open, there is a holonomic constraint $y = 0$, which can be expressed $A_{RO}(q) = (0 \ 1 \ 0 \ 0 \ 0)$ with the corresponding orthonormal null space basis:

$$S_{RO}(q) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

If clamp one is in pivoting position and clamp two is open, there is the same holonomic constraint as above plus the non-holonomic constraint $\dot{x} = 0$. Concatenating both constraints yields the matrices:

$$A_{PO}(q) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad S_{PO}(q) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

In the case where clamp one is in pivoting position and clamp two is in rolling position, there is an additional holonomic constraint that the height of the second clamp is zero: $y - 2L(\cos \theta + \cos \alpha) = 0$, accordingly:

$$A_{PR}(q) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 2L \sin \theta & 0 & 2L \sin \alpha \end{bmatrix},$$

$$S_{PR}(q) = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-\sin \alpha}{\sin \theta \sqrt{\sin^2 \alpha / \sin^2 \theta + 1}} \\ 1 & 0 \\ 0 & \frac{1}{\sqrt{\sin^2 \alpha / \sin^2 \theta + 1}} \end{bmatrix}.$$

When both clamps are in the rolling position, we can remove the $\dot{x} = 0$ constraint, which gives:

$$A_{RR}(q) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 2L \sin \theta & 0 & 2L \sin \alpha \end{bmatrix},$$

$$S_{RR}(q) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{-\sin \alpha}{\sin \theta \sqrt{\sin^2 \alpha / \sin^2 \theta + 1}} \\ 0 & 1 & 0 \\ 0 & 0 & \frac{1}{\sqrt{\sin^2 \alpha / \sin^2 \theta + 1}} \end{bmatrix}.$$

If both clamps are in the pivoting position, we add an additional non-holonomic constraint to $A_{PR}(q)$, that the horizontal speed at the second clamp is zero: $\dot{x} + 2L(\dot{\theta} \cos \theta + \dot{\alpha} \cos \alpha) = 0$ which fully constrains the system except for γ :

$$A_{PP}(q) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 2L \sin \theta & 0 & 2L \sin \alpha \\ 1 & 0 & 2L \cos \theta & 0 & 2L \cos \alpha \end{bmatrix},$$

$$S_{PP}(q) = (0 \ 0 \ 0 \ 1 \ 0)^T$$

The additional three possible clamping configurations can be modeled by an appropriate coordinate transformation and using the above constraint matrices, essentially mirroring the two links. $M(q)$, $F(q, \dot{q})$, and B also change slightly with the coordinate transformation to account for the asymmetry of the SEA.

Finally, we model the torque output τ from the brushed direct current motor linearly as:

$$\tau = \sigma \mathbf{u} - \zeta \omega, \quad \sigma = \frac{\Gamma k_M V}{r}, \quad \zeta = \frac{\Gamma k_M^2}{r}, \quad (5)$$

where σ is the stall torque, $\mathbf{u}$ is the control input (limited to $[-1, 1]$), ζ is the back EMF damping coefficient of the motor, ω is the speed of the motor shaft relative to the motor body (in this case, $\dot{\gamma} - \dot{\theta}$), Γ is the gear ratio of the transmission, k_M is the motor constant, V is the supply voltage, and r is the terminal resistance [9]. Substituting the motor model (5) and moving the $F(q, \dot{q})$ term to the right hand side, we can rewrite (4):

$$S(q)^T M(q) S(q) \dot{v} = S(q)^T \{B[\sigma \mathbf{u} - \zeta(\dot{\gamma} - \dot{\theta})] - F(q, \dot{q})\}. \quad (6)$$

Formulating the Lagrangian dynamics does not yield any insight into the internal forces of the system, such as the

normal force between the clamp and the wire. Since knowledge of such forces is useful for design purposes (e.g. how much force the clamp will have to withstand without opening during a dynamic maneuver and what coefficient of static friction is required to prevent slipping), we can formulate equations for these forces as a function of the state variables (the generalized coordinates and their time derivatives). If clamp one is closed and clamp two is open, the reaction force along clamp one, and its x and y components, are given by:

$$R = m_L \{g[\cos \theta + \cos \alpha \cos(\theta - \alpha)] + L[\dot{\theta}^2 + \dot{\alpha}^2 \cos(\theta - \alpha)]\} \quad (7)$$

$$R_x = R \sin \theta, \quad R_y = R \cos \theta.$$

Note that by design, the clamp cannot exert a reaction torque and may only exert a horizontal reaction force when in the pivoting position.

IV. CONTROLLER DESIGN

We formulated a finite state machine controller to implement all maneuvers listed in section II. Each state has three actions: the positions of the two clamps and the control input $\mathbf{u}$ to the motor. To define the transitions between the states, we limit ourselves to logical expressions with simulated measurements of sensors that are possible on the prototype: the separation angle between the two links, $\theta + \pi - \alpha$, the spring deflection, $\alpha - \gamma$, if a cable is within the grasp of either clamp, and time, see section VI-B. State machines for the four different maneuvers are illustrated in Figs 4-7. The state machines can be practically implemented as a switch structure in most programming languages. The exact values used in the logical expressions and the control input to the motor were determined in simulation.

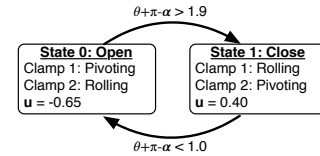


Fig. 4: Inchworm maneuver finite state machine.

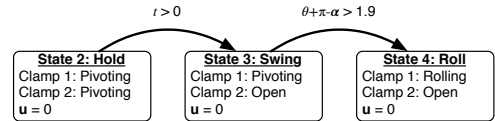


Fig. 5: Swing & roll maneuver finite state machine.

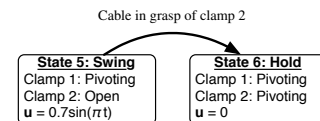


Fig. 6: Swing-up maneuver finite state machine.

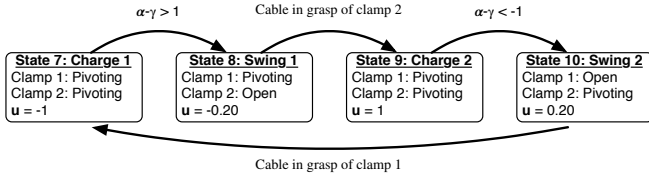


Fig. 7: Backflip maneuver finite state machine.

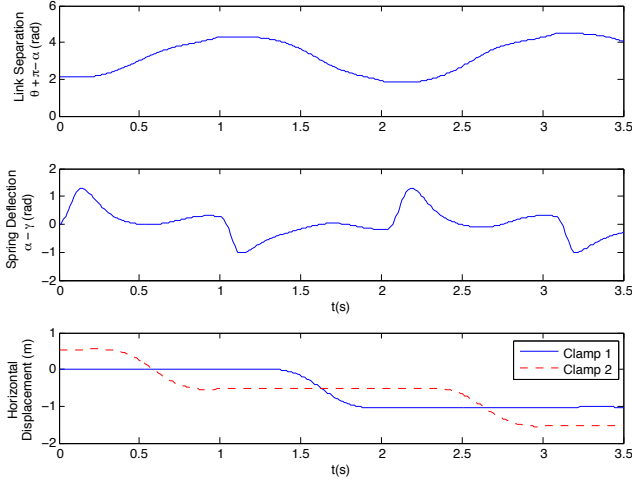


Fig. 8: Simulation results for backflip maneuver.

V. SIMULATION

We created a simulation environment to test the finite state machine controller from section IV with the dynamic equations of motion from section III. We were able to test different parameter values virtually before constructing a prototype. The set of n second-order differential equations (6) can easily be written as $2n$ first-order equations and then marched forward in time from a prescribed initial condition as a switched system dependent on the clamp configuration.

In inchworm mode, the robot alternates which clamp is in pivoting or rolling position. This is treated as an inelastic collision where 85% of the momentum is conserved. Additionally, a delay of 50ms is imposed when switching clamping configurations to account for the time it takes the clamps to physically change positions.

All four maneuvers were simulated successfully, animations are included in the attached video (using parameter values from the prototype). Results for the backflip maneuver are shown in Fig. 8. The maximum dynamic load on the clamp during swinging, from (7), is 6.75N or 1.48g.

VI. PROTOTYPE

In order to validate our positive simulation results, we sought to develop a physical prototype that could be tested in a laboratory setting.

A. Mechanical Design

The prototype is made almost entirely of 3D-printed and off-the-shelf parts. This accelerated manufacturing and enabled more flexibility in the design than traditional machining methods.

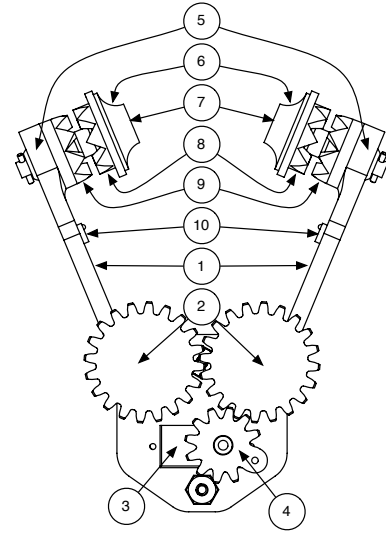


Fig. 9: Clamp mechanism, consisting of 1) arms, 2) coupled spur gears, 3) servo motor, 4) driving spur gear, 5) swivel bearings, 6) rollers, 7) opposite pole magnets, 8) and 9) locking teeth, and 10) infrared LED and phototransistor.

The elbow joint pivotally connects the two links and houses an SEA with a motor and spring system connected in series. The motor is mounted on the first link such that the motor shaft is coaxial with the axis of rotation between the two links. The spring system includes two right-handed torsion springs which are mounted coaxially to the motor shaft. Opposite ends of the springs are rigidly attached to the second link. The motor shaft is rigidly coupled to an intermediate arm which engages one of the two free ends of the torsion springs, depending on the direction of rotation.

The actuated clamp mechanism is shown in detail in Fig. 9, it consists of two arms (1) which are coupled to rotate symmetrically with spur gears (2). A hobby-grade servo motor (3) is used to open and close the arms. A spur gear (4) connected to the output shaft of the servo meshes with the spur gear connected to one of the arms. The servo motor is geared down to increase the torque. The distal ends of the arms house swivel bearings (5), which hold the rollers (6) with a slip fit; there are four degrees of freedom: all three rotational and axial translation. Opposite pole magnets in the rollers (7) align and pull the rollers together. When the two rollers connect, they form a semicircular profile around the top half of the cable. The design is currently optimized for an 11mm diameter. The magnets also provide enough force to prevent the clamp from opening in the event of a power loss. When the clamp is in pivoting position, the arms are rotated to vertical and teeth on the rollers (8) engage with teeth on the arms (9), constraining relative rotation between the rollers and the arms. When the clamp is in rolling position, the arms are rotated far enough apart to disengage the teeth, but the magnets keep the rollers together. In the open position, the arms are rotated far enough to pull the magnets apart. A thin layer of silicone rubber is added to the ABS plastic roller (6) to increase friction. Square polycarbonate

tubing is used to connect the clamps to the joint, wires are routed through the interior of the tube. For the constructed prototype, $m_L = 0.233\text{kg}$ and $L = 0.158\text{m}$ for a total mass of 0.466kg and total length of 0.632m . Other parameters are $J_L = 0.023\text{kgm}^2$, $J_J = 0.0017\text{kgm}^2$, $k = 0.331\text{Nm/rad}$, $\sigma = 0.754\text{Nm}$, and $\zeta = 0.036\text{Nms/rad}$.

B. Electronics

An infrared LED and phototransistor pair are mounted in each clamp to detect when a cable is within grasp, see Fig. 9, (10). One rotary potentiometer measures the angle between the SEA shaft and the first link ($\gamma - \theta$). The second potentiometer measures the angle between the SEA shaft and the second link, which is the same as the angle of the spring deflection ($\alpha - \gamma$). Subtracting the two measurements from π gives the link separation angle ($\theta + \pi - \alpha$), which is useful in the controller. The brushed DC motor in the SEA is driven with an off-the-shelf H-bridge via a pulse width modulated signal. The finite state machine from section IV is implemented on an Arduino Uno microcontroller, which measures the analog sensors and commands the actuators accordingly. We chose a 1000mAh two cell lithium polymer battery for its low mass and high energy density.

C. Results

Data was logged from the prototype while performing the inchworm maneuver on a tensioned rope, see section II-A. Both the simulation and experimental results may be seen in Fig. 10, see also the video attachment. The simulation results match the experimental results, although greater spring deflection is predicted in simulation. Some slipping on the rope occurs while switching clamp positions and the vibrational modes of the rope, which are excited by the movement of the robot, were not included in the simulation. These unmodeled effects contribute to the discrepancy between the plots. The current prototype cannot perform more dynamic maneuvers (swing & roll, swing-up, and backflip) reliably because the clamps can fail under high dynamic loads.

VII. CONCLUSIONS

A novel cable-locomoting robot has been presented with few actuators, but many configurations, which leads to multiple modes of locomotion. The dynamics were derived for the different clamp configurations and finite state machine controllers were developed to perform different maneuvers. Both the dynamics and controller were integrated into a simulation to validate the concept. Finally, a prototype was constructed and shown to behave as predicted in simulation. Compared to existing systems, SkySweeper is smaller, less complex, cheaper, and earlier in the development process. SkySweeper is designed to locomote quickly, and as such may be better suited to applications other than power line inspection, such as entertainment.

In future work, we can use the simulation environment to optimize the spring stiffness, link length, and different maneuvers' control input sequences to minimize the cost of transport, defined as the power required to transport mass

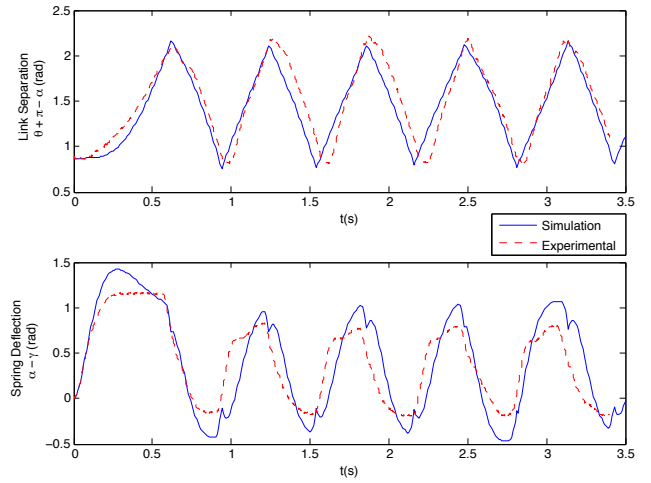


Fig. 10: Comparison of simulation and experimental results for the inchworm maneuver.

over distance. The dynamical model can also be expanded to include the dynamics of the rope including curvature, such as in a suspension bridge. The clamp design will be improved to better handle high dynamic loads and could be modified to enable climbing vertical pipes or rope. Cameras and other sensors for inspection applications can readily be integrated into the robot. Specific to the power line environment, energy could be harvested from the surrounding electric field, which would enable long duration deployments.

ACKNOWLEDGMENTS

The authors would like to thank Victor Ruiz, Amber Frauhiger, Alexandros Kasfikis, and Antonios Kountouris for their assistance in developing the SkySweeper prototype.

REFERENCES

- [1] K. Toussaint, N. Pouliot, S. Montambault, "Transmission line maintenance robots capable of crossing obstacles: State-of-the-art review and challenges ahead," *J. of Field Robotics*, vol. 26(5), pp. 477-499, 2009.
- [2] P. Debenest, M. Guarnieri, "Expliner - From prototype towards a practical robot for inspection of high-voltage lines," *Int'l Conf. on Applied Robotics for the Power Industry*, pp. 1-6, 2010.
- [3] N. Pouliot, S. Montambault, "Field-oriented developments for LineScout Technology and its deployment on large water crossing transmission lines," *J. of Field Robotics*, vol. 29(1), pp. 25-46, 2011.
- [4] Z. Tingyu, Z. Guoxian, J. Jian, "Development of a dual-arm mobile robot for high voltage power lines," *Proc. IEEE Int'l Conf. on Robotics and Biomimetics*, pp. 1924-1929, 2007.
- [5] M. Bühringer, J. Berchtold, M. Büchel, C. Dold, M. Bütikofer, M. Feuerstein, et al. (n.d.). "Inspection of high voltage power lines - a new approach," *Proc. Int'l. Conf. on Climbing and Walking Robots*, pp. 455-462, 2009.
- [6] G. A. Pratt, M. M. Williamson, "Series elastic actuators," *Proc. IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems*, pp. 399-406, 1995.
- [7] N. Morozovsky, C. Schmidt-Wetekam, T. Bewley, "Switchblade: an agile treaded rover," *Proc. IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems*, pp. 2741-2746, 2011.
- [8] K. Pathak, J. Franch, S. Agrawal, "Velocity and position control of a wheeled inverted pendulum by partial feedback linearization," *IEEE Trans. Robotics*, vol. 21, no. 3, pp. 505-513, 2004.
- [9] N. Morozovsky, R. Moroto, T. Bewley, "RAPID: an inexpensive open source dynamometer for robotics applications," *accepted, IEEE/ASME Trans. Mechatronics*, 2013.