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Octopus-Inspired Grasp-Synergies for Continuum Manipulators*

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***Abstract*—Human operation of continuum "continuous-backbone" manipulators remains difficult, because of both the complex kinematics of these manipulators and the need to coordinate their many degrees of freedom. We present a novel synergy-based approach for operator interfaces, by introducing a series of octopus-arm inspired grasp-synergies. These grasp-synergies automatically coordinate the degrees of freedom of the continuum manipulator, allowing an operator to perform kinematically complex grasping motions through simple and intuitive joystick inputs. This effectively reduces the complexity of operation and allows the operator to devote more of his attention to higher-level concerns (e.g. goal, environment). We demonstrate the grasp-synergies interface design in both simulation and hardware using the nine degree of freedom Octarm continuum manipulator.**

Index Terms — Continuum manipulators, user interface, trunk, tentacle, biologically inspired robots.

I. INTRODUCTION

As robotic technology matures and more platforms are fielded in unstructured real-world situations, the importance of a well-designed human interface becomes apparent. For example, most instances of user error observed during robotic operations at the World Trade Center disaster site could be directly attributed to issues with user interfaces [1], [2]. Such evidence motivates the development of innovative user interfaces in order to simplify the task of operating robots and thus reduce the occurrence of human error.

Simple robotic manipulators often use a "one actuator-one input device" user-interface design; which provides the human operator with an individual input device to drive each actuator in the manipulator. While this interface design is easily implementable in a system, it relies on a trained operator to cognitively process low-level manipulator kinematics in real-time. This cognitive burden can distract an operator from their goal and environment and lead to human error.

As the number of actuators and complexity of the manipulator kinematics increases, the cognitive burden this type of user interface places on an operator becomes overwhelming. Consequentially this design scheme is only appropriate for kinematically simple manipulators; typically low degree of freedom, rigid-link manipulators, where the relative position of each rigid link is independently controlled by a single actuator. More complex manipulators require a more sophisticated user interface design.

Traditional rigid link robotic systems have typically dealt with increased manipulator complexity in their user interface by either providing the operator with control over the end-effector's position and orientation [3] or by using biologically-inspired primitives [4], [5], [6]. End-effector space control is unattractive for continuum manipulators due to the complexity of their inverse kinematics. In this paper we introduce a new synergy-based approach for continuum manipulator user interfaces.

Continuum (continuous backbone) robots [7], [8], [9], [10], [11], [12], [13], [14] differ significantly from conventional manipulators in that they bend continuously along their length; as opposed to traditional rigid-link robots, which bend only at fixed locations (i.e. joints). As such, special consideration is required in designing an operator interface for this class of manipulators.

Continuum manipulators typically feature more actuators and degrees of freedom than do their traditional counterparts. For example, the three-section OctArm [15] contains nine actuators; three per manipulator section. Coordinated motion of all three actuators is required to produce useful movement in a manipulator section. By contrast, traditional rigid-link manipulators feature one actuator per rigid link, and as such require no actuator coordination to produce useful movement in a link.

Kinematic analysis reveals further complexity as there is a non-linear relationship between actuator positions and manipulator shape in continuum manipulators [16]. Therefore, a user interface that merely provides control of the individual actuators would prove unusable for an operator, as the cognitive burden of determining manipulator shape based on actuator position would be overwhelming for all but the

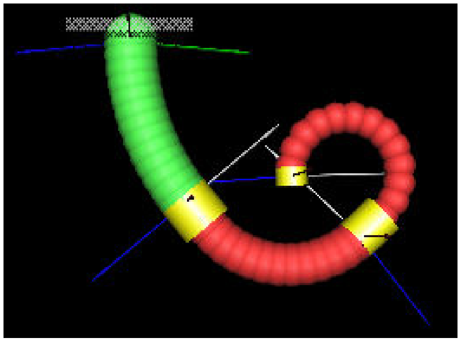

Fig. 1. Graphic simulation of a three-section continuum manipulator.

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simplest of continuum manipulators.

The current user interface for the OctArm continuum manipulator [17] utilizes the kinematic model developed in [18] to automatically perform actuator position to manipulator shape calculations for the human operator. This conversion is critical, as it converts low-level degrees of freedom (actuator positions) to higher-level degrees of freedom (manipulator shape parameters) which are more easily visualized by human operators. However, there are still three manipulator shape parameters for each section, so there has been no reduction in the number of degrees of freedom required for the user to coordinate.

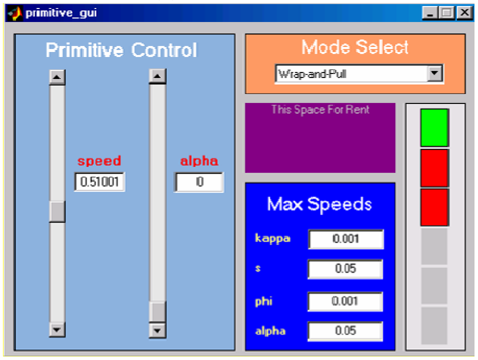
This paper discusses a novel user interface design for continuum manipulators which utilizes octopus-inspired grasp-synergies. This approach to manipulator operation is similar in spirit to previous work with biologically-inspired hand primitives [4], [5], [6]. The synergy functions described in this paper increase the usability of the manipulator by allowing it to be operated in a high-level goal-oriented manner, where the lower-level activity is automatically coordinated. This has the effect of reducing the cognitive burden placed on a human operator, thereby reducing the likelihood of user error. The results are illustrated using the OctArm series of continuum robot hardware for whole arm grasping.

II. OCTOPUS INSPIRATION

One of the difficulties in producing an intuitive user interface for continuum manipulators is that most humans have little natural experience observing such manipulators. Traditional rigid link manipulators at least somewhat resemble human arms, which are observed nearly every day in a person's life, in movement and function. However, continuum manipulators are most closely associated with octopus arms and elephant trunks and are observed much less often and in a less intimate manner by people.

So while human users can draw on their years of experience observing the movement of their arms in forming intuition about the movement of traditional rigid link manipulators, there is no such repository of experience for the formation of intuition regarding the control of multi-section continuum manipulators. Consequently, as octopus arms are the inspiration for many continuum manipulators, it is logical to consider how these biological manipulators are controlled [19], [20], [21] in order to gain insight into harnessing the capabilities of these manipulators.

Recent research suggests that all octopus arm motions can be categorized into three basic arm movement categories: *reaches*, *pulls*, and *searches/gropes/explores* [19]. The *reaches* category refers to behaviors that increase the distance between the arm tip and base. The two specific reach behaviors that have been identified are the uncurling reach, where the arm rolls out, and the elongating reach, where the arm extends. The *pulls* category refers to behaviors that decrease the distance between the arm tip and base. The three specific pull behaviors that have been identified are the continuum curling pull, where the arm rolls in, the straight-arm shortening, where the arm retracts, and the bending pull, where the arm creates an elbow-like bending point. The *searches/gropes/explores* category refers to behaviors that are a lateral combination of sharp bends, lifts, torsion, drop, etc. No specific behaviors have been identified for this category, as the motions seem to be a combination of sweeps, bends, wraps, and torsional rotations.



Wrap-and-Pull

speed 0.51001

alpha 0

kappa 0.001

s 0.05

phi 0.001

alpha 0.05

Fig. 2. Grasp-synergy movement mode graphical user interface.

The fact that octopus arms regularly perform these movements motivates replicating similar behaviors with biologically-inspired continuum manipulators, as they may also prove useful for robot tasks. However, the complex nature of these movements is problematic as trying to replicate these movements with a conventional user interface would require a level of coordination that would prove difficult if not impossible. Fortunately, biology again provides inspiration for a solution.

Biological evidence suggests that animals do not consciously perform low-level coordination of their muscle activity; as such conscious effort would prove to overwhelm even the most cognitively-gifted animal. Instead, animals consciously initiate high level goal oriented actions, where the lower level coordination of muscle activity is performed by the nervous system. In the literature, this coordination of degrees of freedom to perform a motion is sometimes referred to as a synergy [22], [23], [24]. This biological concept motivates the overall concept of allowing many, or all, of the manipulator's degrees of freedom to be actuated with only a small number of simple user inputs [25]. In this paper, the manner in which the manipulator's degrees of freedom are coordinated into a grasping motion in response to simple user inputs is referred to as a grasp-synergy.

III. INTERFACE DEVELOPMENT AND IMPLEMENTATION

Using the biologically-inspired strategy outlined in section II, choices were made to develop modes that take advantage of the smooth exterior and natural compliance many continuum manipulators (including OctArm) feature to perform whole arm manipulation grasping behaviors. Whole arm manipulation allows continuum manipulators to achieve stable grasps with decreased control precision, similar in spirit to the under actuated grasping described in [26]. Note that the inherent compliance of the OctArm manipulators allows them to achieve effective grasping in the presence of significant uncertainty, provided their general preshaping time history is appropriate. The investigated modes were restricted to 2D as biological continuum manipulator grasping actions can largely be reduced to planar motions.

Thus a number of grasp-synergy modes that mimic the reach and pull behaviors of octopus arms have been implemented, as discussed below, both in simulation with a graphics model and in hardware with the OctArm continuum manipulator. These movement modes allow complex multi-section grasp-synergies to be operated with simple joystick inputs. The joystick was chosen as the input device due to its inherent familiarity to operators and ease of implementation. Intuitive joystick inputs were mapped to manipulator movement.

The joystick mappings described in this paper provide velocity control of the grasp-synergy algorithms. As a result, the movements can be easily halted, reversed, or restarted at the operator's discretion. The human operator can also change the speed at which the grasp-synergy algorithms are performed by changing the deflection of the joystick: greater deflections corresponding proportionally to greater speed.

A Matlab-based graphical user interface (GUI) provides a means for observing and modifying operations settings. A screenshot of the GUI is shown in Fig. 2. These operations settings can be modified either through the GUI or by utilizing the joystick button combinations. The GUI provides a drop-down menu with which operators can select which grasp-synergy movement they wish to use to control the manipulator. Text boxes are used to display and configure the maximum speed parameters for the synergy-movements. Additionally, the sliders and text boxes on the left side of the GUI are used to display and configure the speed and α settings of tuned sweep mode, as described in section IV, B. The display on the right side of the GUI provides a graphical display of how the manipulator sections are grouped (i.e. which sections are active, which sections are being "α tuned") and a means of grouping them.

The grasp-synergy movements were developed with the aid of a three-dimensional graphic model of a continuum manipulator, shown in Fig. 1. This graphic model was developed using an OpenInventor-based system which utilizes the Virtual Reality Modeling Language (VRML) [17]. This model can easily be modified to simulate continuum manipulators composed of any numbers of sections, with each section capable of having different physical properties. Thus, movement functions could be quickly tested and theoretically verified for a number of different continuum manipulators without actually requiring the presence of continuum manipulator hardware. This proved to be an effective and efficient practice.

For experiments, the OctArm V manipulator was mounted in a horizontal configuration (shown in Figs. Fig. 3 - Fig. 5). The robot control system (RCS) consisted of a commercial off-the-shelf Pentium III EBX form-factor single board computer and data acquisition electronics for analog and digital I/O. The RCS runs the Clemson University developed hard real-time control software on the QNX® Neutrino® real-time operating system to implement the robot control algorithms. This setup controls the nine electro-pneumatic valves that are used to power and control the actuators of the OctArm manipulator.

The RCS is connected via ethernet to an Operator Control Unit (OCU), consisting of a laptop running Windows® XP interfaced with a USB joystick. The OCU provides a display on which the graphics model provides a real-time 3D visualization of the robot shape to the operator. Additionally, the display features the Matlab-based GUI, described previously. Based on operator inputs from the joystick, the trajectory updates for the robot are computed by a Matlab/Simulink-based program running on the OCU. These trajectory updates are then communicated to the RCS via an Ethernet connection. A similar set-up was used for the Octarm field trials described in [27].

Further details about the implementation of these grasp-synergies with the OctArm continuum manipulators can be found in [28].

IV. PLANAR GRASP-SYNERGY MODES

A. Wrap and Pull Mode

The first of these grasp-synergies modes is the *wrap-and-pull* mode. In this mode the manipulator is divided into two sections: the "wrapping" sections and the "pulling" sections. The wrapping sections are generally chosen to be the more distal sections of the manipulator. The x-axis of the joystick maps to a velocity control of the wrapping sections' curvature. Left on the joystick decreases the curvature of the sections, while right increases the curvature. The y-axis of the joystick maps to a velocity control of the trunk length of the pulling sections. Up on the joystick increases the length of the sections, while down decreases the length. This grasp-synergy simplifies manipulator operation by reducing the dimensionality from 6 to 2.

Using this mode, a continuum manipulator can be made to elongate to reach an object by pushing up on the joystick. The manipulator can then be made to wrap around the object by pushing right on the joystick. The object can then be pulled back toward the base of the manipulator by pushing down on the joystick. The object can then be moved back away from the base by pushing up on the joystick or released by pushing right on the joystick (Fig. 3). These movements correspond to the *elongating reach* and *straight-arm shortening pull* behaviors of the octopus arm.

B. Curling Reach and Pull Mode

The second reach and pull grasp-synergy developed is the *curling reach-and-pull* mode. The joystick buttons can be used to determine whether all or only part of the manipulator will be

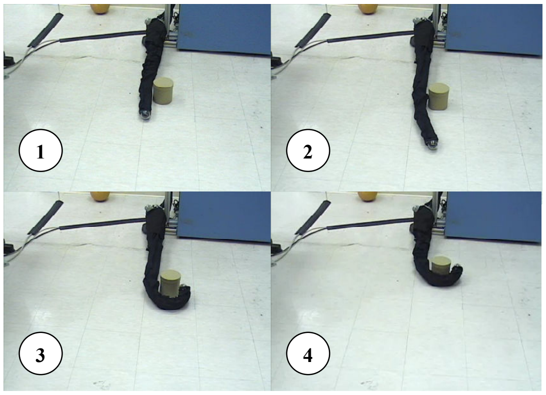


Fig. 3. Implementation of the *wrap-and-pull* planar synergy-movement function on the three-section OctArm prototype. Tip section has been selected as the wrapping section, leaving the other two sections to be pulling sections. User inputs: (1) to (2) joystick up; (2) to (3) joystick right; (3) to (4) joystick down.

used to perform this motion. Generally, the entire manipulator is selected as this movement was conceived as a whole arm motion. For this mode, the x-axis of the joystick provides a velocity control for this movement.

If the selected manipulator sections are in a straight configuration, pushing left on the joystick causes the sections to "curl" to the left. Similarly, pushing right on the joystick causes the section to "curl" to the right. The "curl" motion can be summarized by the following *curl* algorithm:

1. Select the most distal section (e.g. the tip section) that is not at maximum curvature.
2. Incrementally increase the curvature of this section. Go to step 1.

In effect, this algorithm increases the curvature of the tip section until it has reached maximum curvature, then it increases the curvature of the section next to the tip until it has reached maximum curvature, and so forth until the base section has reached maximum curvature. This sequential curvature increase results in a movement that resembles the continuum curling pull behavior of the octopus arm.

If the manipulator sections are already in a curled configuration, pushing on the joystick in the direction of the curl causes further implementation of the *curl* algorithm. However, if the joystick is pushed in the direction opposite the direction of the curl an *uncurl* algorithm is implemented. The *uncurl* algorithm can be summarized as follows:

1. Select the most proximal section (e.g. the base section) that is not at zero curvature.
2. Incrementally decrease the curvature of this section. Go to step 1.

In effect, this algorithm decreases the curvature of the base section until it has reached zero curvature, then it decreases the curvature of the section next to the base until it has reached zero curvature, and so forth until the tip section has reached zero curvature. This sequential curvature decrease results in a movement that resembles the uncurling reach behavior of the octopus arm. Once the curvature of all the manipulator sections has reached zero, the *uncurl* algorithm is halted and the *curl* algorithm is implemented upon joystick x-axis operation.

Using this mode, the continuum manipulator can be driven into a compact curled configuration, by pushing the joystick in one x-direction. From this configuration, the manipulator can be made to reach out to an object by uncurling and to grasp and pull that object into its base by curling in the opposite direction. This complex action can be performed by merely pushing the joystick in the opposite x-direction. This grasp-synergy simplifies manipulator operation by reducing the dimensionality from 6 to 1. See Fig. 4a.

C. *Corralling Sweep Mode*

The first of the sweep grasp-synergies is the *corralling sweep* mode. This mode is in many ways similar to the *curling reach-and-pull* mode. For this mode, the joystick buttons can similarly be used to determine whether all or only part of the manipulator will be used to perform this motion. Generally, the entire manipulator is selected as this movement was also conceived as a whole arm motion. For this mode, the x-axis of the joystick also provides a velocity control for this movement.

If the selected manipulator sections are in a straight configuration, pushing left on the joystick causes the sections to "corral" to the left. Similarly, pushing right on the joystick causes the section to "corral" to the right. The "right" or "left" directions refer to directions of curvature that are relative to looking along the manipulator toward the base. The "corral" motion can be summarized by the following *corral* algorithm:

1. Select the most proximal section (e.g. the base section) that is not at maximum curvature.
2. Increase the curvature of this section.
3. Select the most distal section (e.g. the tip section) that is not at maximum curvature.
4. Increase the curvature of this section. Go to step 1.

The first two steps of this algorithm are the *curl* algorithm. The combined increase of curvature at the base and the tip of the manipulator results in a movement that resembles a slowly constricting hook sweeping across a surface. If the manipulator sections are already in a corral configuration, pushing on the joystick in the direction of the corral causes further implementation of the *corral* algorithm. However, if the joystick is pushed in the direction opposite the direction of the corral an *uncorral* algorithm is implemented. This algorithm is the opposite of the *corral* algorithm and has the effect of practically unrolling the manipulator from a curled configuration in a sweeping motion until the manipulator is again at a straight, zero curvature configuration. Once the curvature of all the manipulator sections has reached zero, the *uncorral* algorithm is halted and the *corral* algorithm is implemented upon joystick x-axis operation.

With this mode, the continuum manipulator can be driven into the same compact curled configuration as the *curl reach-and-pull* mode, by pushing the joystick in one x-direction. However, from this configuration, the manipulator is instead made to sweep out to corral and capture an object by pulling it towards the manipulator's base. This action can be performed by merely pushing the joystick in the opposite x-direction. This grasp-synergy simplifies manipulator operation by reducing the dimensionality from 6 to 1. See Fig. 4b.

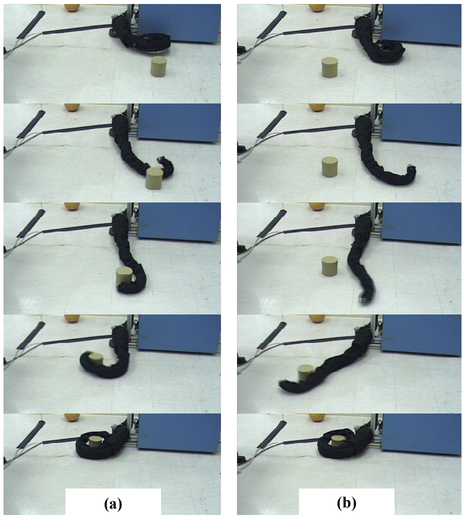


Fig. 4. Implementation of planar grasp-synergy function (a) *curling reach-and-pull* (b) *corralling sweep* on three section OctArm prototype. User input: joystick left. All sections selected to perform movements.

D. *Tuned Sweep Mode*

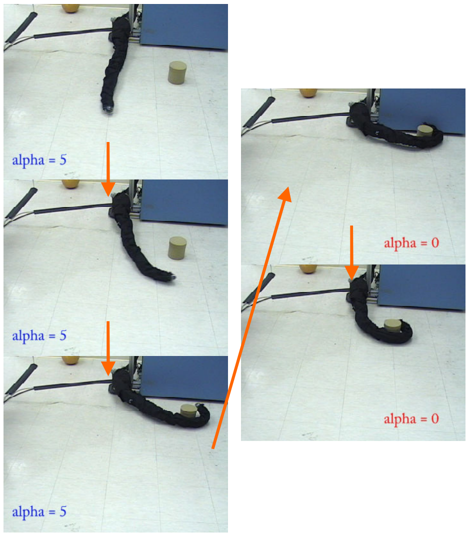
A second sweep grasp-synergy mode, the *tuned sweep* mode, was also developed. This movement mode involves the whole-arm. In this mode, the x-axis of the joystick maps to a velocity control of the manipulator sections' trunk curvature, with left on the joystick decreasing the trunk curvature of the sections and right increasing curvature. Currently, the direction of curvature is fixed to the left. The joystick buttons are used to select which sections of the manipulator are subject to the tuning parameter α, which controls the curvature bending speed of the selected sections relative to the other sections.

If $\alpha = 1$, the tuned sections move at the same speed as the rest of the manipulator sections. However if $\alpha < 1$, then the tuned sections move at a speed that is slower than the other manipulator sections; if $\alpha > 1$, then they move at a speed that is faster. For instance, if $\alpha = 0.5$ then the tuned sections change curvature at half the speed of the rest of the manipulator. If $\alpha < 2$ then they change at double the speed. If $\alpha = 0$ then the tuned sections do not change curvature at all. Being able to set $\alpha = 0$ is useful once an object has been grasped, as it allows the grasping sections to be "locked down", while the other sections can still be used to move the grasped object around. The value of α can be altered with the hat switch of the joystick, with up mapping to an increase in α and down mapping to a decrease.

This grasp-synergy mode allows an operator move the manipulator in a sweeping manner to capture an object by pushing right on the joystick. This is a similar motion to the *corral sweep*; however, the tuning parameter α provides the user greater control over the shape of the manipulator during its sweeping motion. This grasp-synergy simplifies manipulator operation by reducing the dimensionality from 6 to 2. See Fig. 5.

E. *Discussion*

All of the above synergies proved highly successful in terms of reported operator satisfaction and speed of grasping. Previous OctArm grasping operations, in configuration (section) space, required significantly higher concentration on low-level details on the part of the operator, and typically resulted in much longer times to grasp (often on the order of minutes, as opposed to seconds with the synergies). Based on these results, we believe that synergies should form a key subset of the modes available to operators of continuum robot technology in the future.



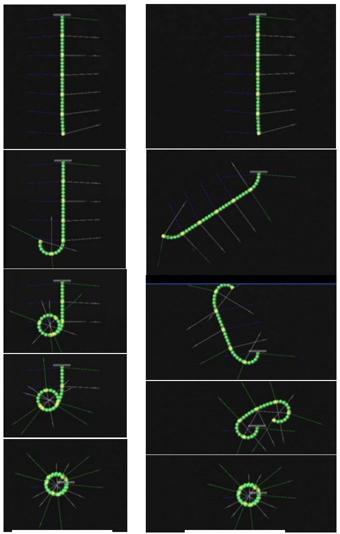
(a) (b)

Fig. 5. Implementation of the *tuned sweep* planar grasp-synergy function. Tip section is selected for tuning. (a) Tuning parameter $\alpha = 5$, User input: joystick right. Note that tip section curves 5 times faster than other sections. (b) Tuning parameter $\alpha = 0$, User input: joystick left. Note that tip section does not uncurve at all.

V. CONCLUSION

The novel biologically-inspired octopus-mimicking grasp-synergy functions introduced in this paper increase the usability of continuum manipulators such as the OctArm by providing users with an interface that allows them to easily perform complex grasping motions in an intuitive fashion with simple inputs. While the user-interface modes described in [17] allow the manipulator to be driven into any physically possible configuration, the user interface mode described in this paper restricts the manipulator to motions that are useful for achieving grasps. This dimensionality reduction allows users to shift their attention from low-level coordination of the manipulator shape parameters in order to concentrate on higher-level goal behaviors.

The grasp-synergies user interface mode has the added benefit of being inherently scalable. Increasing the degrees of freedom of the manipulator by attaching additional manipulator sections does not increase the complexity of the grasp-synergy user interface. In simulation, the movements have been found to operate in the same expected manner for manipulators with three to six sections (Fig. 6). The scalability of this user-interface is in stark contrast to the non-synergy based operation modes where the complexity of the user interface increases exponentially as the degrees of freedom of the manipulator increases. Additionally, the grasp-synergies are theoretically generalizable to different continuum manipulators, allowing for modifications that may be needed to account for particular



(a) (b)

Fig. 6. Implementation of planar grasp-synergy function (a) *curling reach-and-pull* (b) *corralling sweep* on a six section continuum manipulator simulation. User input: joystick left. All sections selected to perform movements.

hardware eccentricities.

A framework was developed that simplifies the creation of synergy-movements. These include primitive functions which provide individual access to low-level manipulator parameter degrees of freedom. These functions operate within the framework in such a way that they can be easily combined in a coordinated fashion to create the complex synergy-movements. The behavior of synergy-movement algorithms in development can be observed in the graphic model which is able to simulate the behavior of virtually any continuum manipulator. In this way, the generalizability of the algorithms can be verified. Additionally, a graphical user interface has been developed which displays pertinent information for the operation of the synergy-movement functions. The GUI also allows adjustment of parameters that affect the behavior of these functions.

Inspiration for the development of further synergies could come from observation of other biological manipulators, such as elephant trunks. Synergies could also be made more powerful with environmental sensing. Synergy movements could be made to automatically trigger due to environmental cues. For instance, if an object were to touch the manipulator, a synergy could be developed either to automatically ensnare that object or to move the manipulator arm away from the object. The availability of such "reflex" behavior would further simplify manipulator operation.

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