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VIRTUAL SOFT ROBOT OPTIMIZATION AND EVOLUTION RESEARCH PROPOSAL

By

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EXECUTIVE SUMMARY

Title: Virtual Soft Robot Optimization And Evolution

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Description And Aims:

The project will involve testing various types of virtual soft robot evolution, optimizing a particular type by specifying and optimizing unit cell behaviour for this method, applying the optimized process to obtain workable results, and implementing the process as an easily modifiable and reusable process.

Unique Research Contributions:

An easily modifiable software implementation that can be used for future research into the evolution of virtual soft robots.

Study Time Framework:

The main components of the project will be an extensive literature review, implementation and testing of existing approaches to evolving virtual soft bodies, optimization of and assigning properties to unit cells, application of the optimized cells to a certain evolution approach, and implementation of this application in such a way that it is reusable and modifiable. A complete Gantt chart of the time framework can be found in Appendix A.

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Declaration

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This assignment is my own work.

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1. INTRODUCTION

1.1. BACKGROUND

The field of soft robotics is relatively new with many potential areas of exploration. A particular area of interest is the design of the physical form of soft robots. Due to their compliant and imprecise nature, coming up with accurate and specific designs is often difficult. Additionally, there is a lot of potential for unexplored design spaces to yield interesting and potentially useful results.

A well-known method of exploring large and unknown design spaces is the application of genetic algorithms. These algorithms can be adept at finding interesting, original and seemingly unintuitive solutions to given problems. Application of specific genetic algorithms to the design of soft robots may yield useful and insightful results that may otherwise be impossible to create manually.

However, a potential problem with this application is the computing power that may be required. Due to the complex nature of soft robots' physical forms and behaviours, and the necessity of multitudes of populations and generations for better results from the genetic algorithms, processing and storage of data may quickly become too costly. Optimization of the virtual soft robots is thus a necessity.

Thus it is desirable to find a way to optimally model and evolve virtual soft robot bodies capable of completing specified tasks, and to implement it in such a way that the process can easily be modified and used for further development.

1.2. RELEVANCE

Soft robotics are a primarily mechanical and mechatronic field, due to the materials science, design, manufacturing and control involved. Dr. Martin Venter and the MOD research group deal with soft robotics and their design, and thus investigation into potential design solutions has some relevance and purpose.

2. OBJECTIVES

The research objectives are to:

- Explore existing attempts to virtually evolve soft robots
- Optimize the modelling of the properties of building blocks or unit cells that could be used to virtually model soft robots and potentially be physically constructed
- Implement the optimized blocks or cells with the most appropriate virtual evolution method
- Run simulations to determine the performance of the new implementation
- Set up the implementation and simulation process so that it is easily modified and reusable

3. MOTIVATION

Gaining understanding of existing attempts to virtually model and evolve soft robots may lead to a deeper understanding of potential flaws and areas for improvement, as well as which method seems most promising and most suitable for the purposes of this project.

The optimization of the unit cells is crucial to the optimization of the simulation, which can easily be very resource-intensive. Additionally, little progress has been made in this area, with most existing approaches simply utilizing existing architecture in the software to model the soft robot components. Assigning properties that are linked to real-world properties may lead to more viable designs, where most existing results are not necessarily physically replicable in a sensible manner.

Setting up the software created for the project to be reusable and modifiable will hopefully lay the groundwork for future research. Instead of having to replicate existing projects, much time can potentially be saved by setting up user-friendly software that will allow for easy exploration of different input conditions, material properties and testing goals, upon which further research can easily be built.

4. LITERATURE REVIEW

4.1. SOFT ROBOTICS

4.1.1. CONTEXT

Soft robotics is a relatively new area of study and development in the field of robotics. Soft robots differ from traditional hard robots in that they consist of components that are much more compliant and pliable in nature. Additionally, where hard robots generally have joints at which locomotion occurs with rigid sections in between, soft robots generally have fixed joints with the sections between causing the locomotion (Whitesides, 2018).

There are many benefits of soft robots over hard robots, such as increased safety around humans. Where hard robots are heavy, rigid, and often move with great speed and force, soft robots are generally much lighter, more pliable and as of yet, do not move with dangerous speed and force. Not only does this make them safer around humans, but also more ideal for working with fragile objects and materials. They also require lower tolerances for accuracy in manufacturing and usage, as by their nature they are less precise. Contrastingly, hard robots require much higher tolerances in their design and manufacture, as there is little room for error in their motions. They are also generally lighter than hard robots of a similar size, which could be useful in many cases (Whitesides, 2018)

4.1.2. TYPES OF ACTUATORS

Actuators are components that cause controlled motion, generally used in robotics and machinery (Sekhar and Uwizeye, 2012) There are currently a few prominent types of soft robot actuators in use (Boyratz, Runge and Raatz, 2018).

4.1.2.1. SHAPE MEMORY ALLOYS

Shape Memory Alloys (SMA) are metallic alloys that can be formed into a certain shape above a specific transformation temperature, and then reformed into another shape below that temperature. When the material is heated above the transformation temperature again, it reforms into the first shape, and if the temperature is lowered, it will recover the other shape. This property is the result of the transition between the martensite phase of the material at the lower temperatures, and the austenite phase at the higher temperatures. In SMA actuators, heating is done by applying a current directly to the material. SMA actuators are small, lightweight, have a high force-to-weight ratio, and are silent. In a straight shape they can exert powerful forces but only achieve small displacements relative to their length. When coiled they can extend much more but exert smaller forces (Villoslada *et al.*, 2015).

4.1.2.2. SHAPE MEMORY POLYMERS

Shape Memory Polymers (SMP) are similar to SMAs, but where SMAs are generally comprised of metallic materials, SMPs are built from smart polymers. They have same shape memory property as SMAs. The initial shape is determined and obtained during the manufacturing of a particular element. Most current SMPs also use a temperature transition as the transformation mechanism. The element is then cooled and formed into another shape. When this shape is heated above the transition temperature, it reforms into the original shape, and when it cools down it returns. SMP actuators may use electricity or light as a heat source (Behl and Lendlein, 2007). They have high deformation capacity and shape recovery. They are also much lighter, cheaper, and easier to produce than SMAs. However, they are generally limited in size, as they have low recovery stresses (Rodriguez *et al.*, 2016).

4.1.2.3. DIELECTRIC/ELECTRICALLY-ACTUATED POLYMERS

Dielectric/Electrically-Actuated Polymers (DEAP) use layers of polymers interspersed with conductive material, which, when provided with an electrical input, cause a chemical reaction that results in a volume change across the layers. The layers then bend in a particular direction. DEAPs are low on energy consumption, weight and noise production. They are also biocompatible and can work underwater. Their properties make them well-suited to mimic the traits of natural muscles. However, their reactions under higher voltages are not entirely understood yet and modelling them accurately is a complicated task (Mutlu *et al.*, 2014).

4.1.2.4. ELECTRO-MAGNETIC ACTUATORS

Electro-Magnetic Actuators (EMA) make use of magnetic microparticles in a polymer matrix, which are then manipulated to cause motion by an external magnetic field from an electromagnet. This allows for a wide range of motion by simply varying the orientation and magnitude of the magnetic field. The actuators are typically small with good power efficiency and require relatively low voltages. They have quick response times and high dynamic ranges. They are, however, still in the early stages of development (Do *et al.*, 2018)

4.1.2.5. FLUID ELASTOMERIC ACTUATORS

Lastly, Fluid Elastomeric Actuators (FEA) use soft polymeric structures with internal geometry that causes predetermined motion when driven by fluidic pressure. The fluid pressure may originate from high pressure containers or chemical reactions. They are relatively simple to design, produce, and control, and are lightweight and potentially inexpensive. By their nature, they can easily be scaled to multiple different sizes, and are resistant to many forms of damage (Shepherd *et al.*, 2011; Onal *et al.*, 2017)

4.1.3. SHAPES OF ACTUATORS

A common actuation method is linear extension, which can both be achieved with multiple types of soft robot actuators, and has many applications, such as increasing reach or activating switches. A similar method is torsional extension, which can also be achieved with multiple types of actuators. It differs in that where linear actuators expand or contract directly linearly, torsional actuators twist as they extend, meaning there is some angle of twist occurring between the ends (Whitesides, 2018).

A more versatile actuation method is curling. FEAs can be structured to curl on contraction and straighten out on expansion. This motion is similar to natural muscle contraction, and has a range of applications, especially when used in conjunction with multiple actuators. One use is as a gripper, where multiple FEAs of this type are arranged similar to the structure of a hand or a group of tentacles, with all curling inward. This gripper structure may then be used to pick up and manipulate objects or hold on to structures to climb (Whitesides, 2018).

4.2. EVOLVED VIRTUAL BODIES

4.2.1. GENETIC ALGORITHMS

Optimization of discretely represented mathematical model problems is an active area of research. A robust approach to solving these problems is the use of genetic algorithms. Genetic algorithms are named as such due to their similarity to the evolution of biological creatures. A typical genetic algorithm may start off with a randomly generated population of solutions to a given problem. These solutions' suitability to solving the problem are each checked and the better solutions are used to generate a new population, through combination of these solutions in semi-random ways. The new solutions' suitability are then checked again, and this process is repeated for a specified amount of

generations, hopefully having achieved an appropriate solution (Groenwold, Stander and Snyman, 1999).

Genetic algorithms are very versatile, being applicable to optimising functions as well as evolving complex behaviours and bodies. They are often applied in the evolution of robotic bodies (Sims, 1994b, 1994a).

One approach to genetic algorithms involves the use of Lindenmayer systems. Lindenmayer systems are used in theoretical biology to describe and simulate natural growth processes, based on a hierarchical grammar, which makes them particularly suitable for describing fractal structures. The grammar structure is useful, as its rules can be used to generate strings which then inherently follow the rules of the grammar. These strings can essentially be used as the DNA of whatever you are evolving. This thus allows for very good control over what is allowed to evolve (Kolodziej, 2002).

Genetic algorithms are of no use if there is no measure of performance. Each generation needs some metric to be tested against. In the context of virtual bodies, a physical target is often set, such as distance travelled in a certain direction within a limited time frame. Additional measures of fitness may also be applied, such as the energy requirements, size, and complexity of the resulting body. Thus bodies that perform well against these targets and metrics may be favoured for surviving or procreating, depending on the evolutionary algorithm chosen (Sims, 1994b, 1994a).

An interesting phenomenon that is often prominent when working with evolving virtual bodies is that of emergent properties. Complex behaviours that are usually not well understood initially, arise from the combination of simple elements and rules. With evolving bodies, this may be illustrated by the elements, e.g. muscles, bones, joints, and the rules, e.g. motion limits, interaction between elements, which are relatively simple at first, resulting in complex organisms with methods of motion and behaviours that are not well understood without in-depth analysis (Damper, 2000). This is desirable, as a goal of evolving virtual bodies is to arrive at designs that are original, unique and perhaps even not possible to be conceived of by the human mind, at least easily (Sims, 1994b).

In 1994, Karl Sims introduced the concept of evolving three dimensional virtual creatures using genetic algorithms. The creatures adapted and evolved according to specified fitness evaluation functions, which, in this study, were swimming as far as possible in a limited time, walking as far as possible in a limited time, jumping as high as possible from a standing position, and following a light source as best they could. The creatures were modelled simply, with nodes describing rigid parts of the body, including their dimensions, the type of joint between a part and its parent part, the joint's limits of motion, neurons, and the set of connections the node has to other nodes. These connections have their own sets of information, describing a part's relationship to its parent. These creatures, as described by multiple nodes, are then evolved in three dimensional virtual environments using genetic algorithms for a specified number of generations, after which the best models were selected and inspected. Sims also performed further tests where multiple creatures were evolved in the same environment with a competitive goal. The creatures had to keep a cube as close to themselves and as far away from the opposing creature as possible. This was done to further investigate the effect of competition has on evolution and how it could potentially optimise these creatures even further. Interesting creature morphologies came about through these tests (Sims, 1994b, 1994a).

4.2.2. EMERGENT PROPERTIES

Emergent properties are the result of combinations of simple behaviours that result in much more complex behaviours (Damper, 2000). Much research has been done studying emergent properties of various systems, such as Southwell, who used deterministic systems as opposed to the commonly

used probabilistic, in order to investigate these complex properties more successfully (Southwell, Huang and Cannings, 2013).

4.2.3. PREVIOUS APPLICATIONS TO SOFT ROBOTICS

In 2013, Cheney et al applied Sims' evolutionary approach to design to the field of soft robotics. Building models from voxels in the free VoxCAD software, they evolved these models using CPPN-NEAT, a compositional pattern producing network, similar to a neural network. They found that the CPPN morphologies appeared natural and produced interesting and varying results. They used three types of materials with three defined hardnesses, being representative of compliant, partially compliant and stiff materials. The model tasks were either traversing a linear path or through a tight space, but simulations were run multiple times with differing penalty functions to inspect the effects these had. The penalty functions included were a cost for actuated (i.e. soft) voxels, a cost for voxel connections, a cost for the total number of voxels and no cost. Different forms performed better under the different cost functions. The resulting models are capable of being 3D printed, but the resulting physical model can only be actuated by placing it inside a pressure chamber where the pressure is varied, causing locomotion of the model, which has its limitations in practice (Cheney *et al.*, 2013; Cheney, Bongard and Lipson, 2015).

Another approach was followed by Rieffel et al in 2012. Instead of the aforementioned voxels, they made use of tetrahedral meshes, modelled in NVidia's PhysX engine, as the basic structural element of their soft bodies. The physical properties of the tetrahedral components were defined using this physics engine's settings, which allow for manipulation of a material's stiffness and damping coefficient. They controlled their evolution by fixing one of three properties and allowing the other two to evolve; these properties being the body shape, body motion and material properties. They could also manipulate the mesh resolution. A higher resolution would cost more computing power, but result in smoother surfaces, and vice versa. Once again, the models are 3D printable, but lack a simple actuation mechanism (Rieffel *et al.*, 2013)

Both of the previously discussed approaches used simplified geometry to represent soft robots, but this results in less useful models, as soft-bodied robots would ideally have smooth surfaces. Modelling perfectly smooth surfaces using the previous two techniques would not really be possible, but Hiller and Lipson in 2012 modelled soft amorphous bodies using the Gaussian mixtures representation. This representation method lists Gaussian points in a 3D workspace, with associated densities and falloff ranges. This results in smooth, freeform shapes as opposed to the edged structures in the two previously discussed methods. Material properties are stored in the Gaussian points and distributed accordingly between points. These shapes are efficiently stored and represented, and then can be evolved similarly to the other methods, with the parameters of interest or genomes simply being the points' coordinates, density, falloff range and material index (Hiller and Lipson, 2012).

5. PLANNING

5.1. RESEARCH AND LITERATURE REVIEW

An extensive literature review was done for the purposes of understanding the field of study and relevant adjacent fields; obtaining context for the problem at hand and potential solutions and approaches; and gaining deeper insight to and familiarity with the relevant fields of study.

Although the primary literature analysis was done for the proposal, continuous evaluation of new literature as well as re-evaluation of previously viewed literature will be done throughout the project.

5.2. EXISTING SOLUTIONS

Existing solutions as implemented by Cheney, Hiller and Rieffel will be replicated as far as possible, by using what they have made publicly available and recreating or modifying as necessary. This will be done on a smaller scale, with smaller populations and less generations, as the intended purpose is to gain deeper understanding, and determining which approach would be best to follow for the rest of the project.

5.3. UNIT CELL BEHAVIOUR AND OPTIMIZATION

Taking into consideration the approach chosen during the previous phase, a number of unit cells will be defined. These cells will have specific behaviours which, when combined into larger clusters, will exhibit desirable properties as being representative of existing or potential soft robot actuators and other structural components potentially part of soft robots.

Once these behaviours are appropriately defined, the cell structures will be optimized for modelling purposes, so that they require as little processing and storage capacity as feasible, in order to minimize simulation costs.

5.4. IMPLEMENTATION

With these unit cells so optimized, they will be implemented using the evolutionary algorithm selected from the Existing Solutions phase. Having been implemented, a full simulation will be run using the resources of the CHPC supercomputer, as described more in detail in Equipment And Software in Chapter 6. Once the simulation has been run satisfactorily and usable results have been obtained, these results will be analyzed and inspected to ensure validity and usefulness.

5.5. SOFTWARE SETUP

Once the results of the implementation have been verified and approved, the existing software will be reused to set up software that allows for intuitive, user-friendly implementation with easy modification

5.6. FINAL REPORT

Once all practical components of the project are complete, the write-up of the final report will be done. Meticulous notes and records will be kept throughout the project of progress, activities, complications, solutions, interesting occurrences and data obtained. These notes and records will be used in the construction of the final report.

5.7. GANTT CHART

The Gantt chart may be found in Appendix A.

6. FACILITIES REQUIRED

No external funding covering the research project is available, thus project expenses will be largely limited, using mainly what is already accessible at the faculty and owned by the researcher.

6.1. PHYSICAL FACILITIES

Since the research project will be software-based, little is required in the way of physical facilities. An office setup in the Mechanical Department is provided and will be adequate for the intended use.

6.2. EQUIPMENT AND SOFTWARE

A personal computer owned by the researcher as well as the Engineering faculty computers in FIRGA will be used as required for the project. Software use will be limited to licensed software already obtained by the University, or free software available to download.

In order to run larger simulations, usage may be made of CHPC resources, which are freely available to academic researchers provided they have followed required registration steps properly and submit requests appropriately.

6.3. BUDGET

The budget only takes into consideration the hours worked on the project and the cost of equipment already available. The complete budget may be seen in Table 1 and Table 2 below.

TABLE 1: TOTAL BUDGET

Expense	Cost
Engineering time	R 1 680 000.00
Equipment cost	R 15 000.00
Total cost	R 1 695 000.00

TABLE 2: ENGINEERING TIME BUDGET

Hours per week	60
Total weeks	80
Total hours	4800
Hourly rate	R 350.00
Total	R 1 680 000.00

7. RISK ASSESSMENT

There is little risk associated with this project.

The project is run independently from other students' work, so there is no dependence on other parties for progress.

With good planning and timely requests, the risk of not obtaining access to required services can be mitigated as much as possible, barring complete failure of the services or their availability, in which case if planning was done well, research can be done in order to find alternative services. Additionally, the Gantt chart in Appendix A has some allowance for delays in the project, as a much longer than needed time period is allocated for the writing of the report.

Since the project has no external funding attached, there is no risk of the loss of funding either.

No ethical clearance or protocol is required for this research project, as no testing involving humans or other living beings will be performed.

8. PROGRESS TO DATE

The literature review and research have been completed so far, although further reading will be done throughout the project.

The VoxCAD software has been installed and the online tutorials completed in order to gain familiarity with the software.

Python experience has been obtained through another course presented during this semester and some online tutorials' completion as well.

All preparations for the project as already required for the proposal have been completed, such as the objectives, planning and risk assessment, although these may be adapted if necessary as the project progresses.

Progress was mainly limited to preliminary phases of the project, due to time limitations caused by the coursework required by the other modules taken during the first semester.

9. CONCLUSION

In conclusion, the research project proposed should be completed by the researcher with the aid of the supervisor as necessary in the time specified in the Gantt Chart in Appendix A, which has allowance for extra time should unforeseen circumstances delay the project in any way.

Only preliminary progress was achieved so far, but essential skills were learned during the coursework of the first semester, which should prove valuable in the completion of the project.

It is expected that the objectives will be achieved to an acceptable degree of success, resulting in an optimized, reusable system for the evolution of realistic soft robots.

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APPENDICES

A. GANTT CHART

