Design and Fabrication of an Elastomer Based Variable Stiffness Device

David Altmann, Benjamin Massow, David R. Clarke

Abstract—**Elastomer Based Variable Stiffness Devices are a new type of actuator with great potential for a wide range of applications in soft robotics, exoskeletons, gripper technologies and in various medical devices due to their extraordinary fast change of state from hard to soft and vice versa. All these applications can have an impact in tools assisting and helping humans that either require medical support, or humans that need support while performing work – (e.g. on construction sides, prostheses, walking assistance or lifting devices). The implementation of such an actuator enables their users to perform activities that were previously difficult or partially impossible. Likewise, it allows them to use new actuators that exceed the movement limits of conventional actuators and protect the body from overexerting working conditions. In order to develop such a sophisticated device, many aspects during the material selection phase have to be taken into account. The basis of the material selection process is the experimentation with the so-called "Single Fiber Pull-Out Test" and the "Three-Point Beam Test", that allow to gather valuable information about the behavior of an elastomer and fiber composite. These tests are done with and without the presence of UV-light, which allows the composite material to soften click-wisely when turned on, and to be stiff when turned off. By analyzing the obtained results, the most fitting material is chosen for the design of a prototype that shows the basic features. It turns out that through careful testing, an elastomer reinforced with glass fibers is found to meet the criteria of a novel actuator. An easy-to-make first prototype is produced whose improvements will be incorporated and further investigated.**

Index Terms—**Soft-Robotics, CAN-Materials, Medical-Technologies, Elastomers, Materials Selection**

D. Altmann studies at MCI | The Entrepreneurial School© and Harvard University, e-mail: daltmann@seas.harvard.edu d.altmann@mci4me.at.

I. Introduction

THE production of precisely controllable Variable Stiffness Devices (VSDs) is important in various scientific fields such as soft-robotics and medical technologies. One of the most important goals is to provide adequate medical care for people in hospital care and further treatments. While great progress is made in scientific research to meet this need, further development, detailed elaboration, and extensive testing are required to overcome the many challenges and difficulties in this field. By actively addressing these challenges, a variety of benefits, such as improved automation capabilities and advances in miniaturization are ensured. A revolutionary class of VSDs emerges that is capable of significantly expanding the scope of applications and opening up breakthrough opportunities, particularly in the area of soft-robotics. A new material composition is achieved through the combination of newly developed elastomers and so-called Covalent Adaptive Networks (CANs) that must be further investigated. This breakthrough enables rapid state changes within the actuator and provide precise control [1]. In addition, these actuators exhibit fast and accurate responses, making them suitable for use in time-critical areas such as surgical procedures. One of the main goals of this project is to find the ideal material composition of the materials shown in Table I, in order to develop an endoscope, similar to Figure 1 that works as an elastomer based VSD. This innovative approach holds potential to revolutionize medical procedures by providing surgeons with a versatile tool that can dynamically adjust its stiffness.

Fig. 1. VSD as an endoscope [2].

The first material in Table I is abbreviated by "Low"-, the second as "Middle"-, and the third as "High"-material which is referred to the corresponding G-moduli.

TABLE I
ELASTOMER AND FIBER MATERIALS USED FOR MATERIAL SELECTION PROCEDURES

Elastomer Materials	Fiber Materials
V32/1V3T/SMS22/25SM21	Nylon
PDV/1V3T/SMS42/25SMS22	Glass
V22/1V3T/SMS42	Steel

The ability to adjust the stiffness of an endoscope during examinations or procedures can greatly improve maneuverability and allow for more effective navigation through complicated anatomical structures while minimizing patient discomfort and preventing potential injuries.

II. METHODS

Two types of experiments, namely the Single Fiber Pull-Out Test and the Three-Point Beam Test, are conducted under varying UV-intensities to evaluate the composite behavior and assist in the final material selection process. The Single Fiber Pull-Out Test assesses the stiffness k and interfacial bond strength τ between the fiber and the matrix material, while the Three-Point Beam Test measures flexural strength and stiffness [3], [4]. These experiments provide valuable insights into the mechanical properties of materials, especially the stiffness, enabling to gather information of stiffness ratios Ψ and total differences Δ. With that, a shortlist of composite materials can be made and therefore the preliminary material selection. Once this shortlist is compiled, the Three-Point Beam Tests can be examined. These tests focus on the material compositions shortlist and are tested with varying fiber densities (FD) as well as UV-intensities. Its goal is to investigate the highest values of Ψ and Δ for finding the biggest changes in k and enable the final material selection for the elastomer based VSD. The reason for the materials chosen in Table I is that the corresponding G-Moduli are selected in a way that significant differences in magnitude between the elastomer materials are as great as possible to see the differences in behavior more obviously. A similar approach is used for the fibers: three fibers (glass, steel, and nylon) with different characteristics are used to cover a large range of possible behaviors.

A. Single Fiber Pull-Out Test

The Single Fiber Pull-Out Test is one method to investigate the bonding strength between an embedded fiber and a matrix [3]. Its basic structure can be seen in Figure 2. This test method finds various applications in the field of material science, especially in the examination of fiber and elastomeric matrices [5].

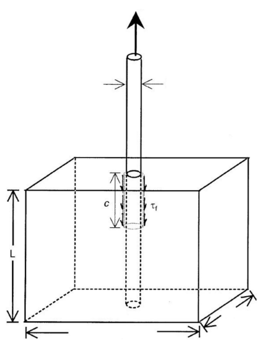

Fig. 2. Basic structure of the single fiber pull-out test [3].

By this experiment, the interfacial properties such as the interfacial shear strength τ, and frictional stress σ_f can be described in more detail [4]. A round fiber with a given diameter d is embedded in a cube-like matrix of a material. This diameter is not necessarily specified, any diameter can be used and must be taken into account in the data analysis afterwards. Typically, the fiber is held by two clamps and the matrix is fixed on the other side by an embedding. The embedding is a mold, where the matrix material is poured in and gets solidified with a respective method. The materials used in the matrix in this project are all elastomers.

B. Experimental Setup – Single Fiber Pull-Out Test

The experimental setup is shown in Figure 3. To achieve reliable and reproducible test results, certain test parameters have to be defined. The consistency of the data is of highest importance to be able to make a fundamental pre-material selection. The acceleration of $100\,\mathrm{mm\,s^{-2}}$ is relatively high in order to transition to a constant speed of $0.1\,\mathrm{mm\,s^{-1}}$ immediately which is kept at a very low speed to reduce noise and let the composite material adapt to the displacement and deformations. To ensure the complete separation of the fiber and elastomer matrix, a distance of $11\,\mathrm{mm}$ is used for the experiments without UV-light. A bigger distance must be used for the experiments with UV-light, because the composite material changes its behavior drastically and can also get softer, which is why greater distances must be covered. The last parameter is the intensity of the OmniCure© S2000 with an intensity of 30 $\mathrm{W\,cm^{-2}}$. When conducting the experiments with UV-light, one test each with $1\,\%$, $5\,\%$, and $10\,\%$ of the maximum intensity is carried out.

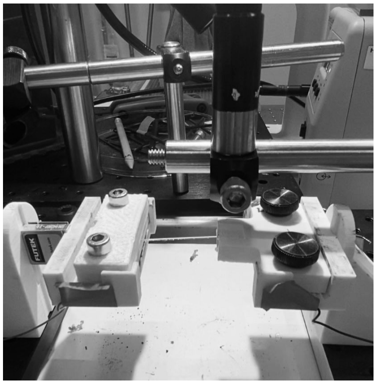

Fig. 3. Final experimental setup – single fiber pull-out test.

In the right part of Figure 3, the test mold is fixed in the embedding, the left part shows the clamp-mounting is where the fiber is fixed in between. The UV-illumination is coming from the top and shines directly onto the composite material to change the chemical and mechanical composition. Its results are plotted in a force-displacement diagram and analyzed for the preliminary material selection.

C. Three-Point Beam Test

A different experiment to determine the composite material's properties is the "Three-Point Beam Test". The basic experimental setup for this experiment is illustrated in Figure 4.

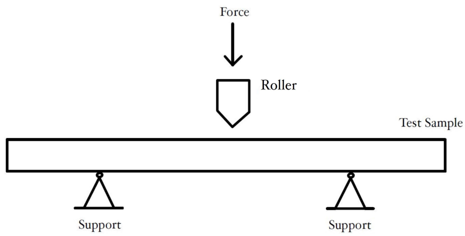

Fig. 4. Schematics of a basic three-point beam test.

In this experimental setup, the focus is mainly on the material's respectively composites' stiffness that can be calculated with

$$k = \frac{F}{x} \tag{1}$$

where F is the acting force and x the displacement. The corresponding values are measured by the force sensor of the respective experimental unit and are plotted in a Force-Displacement diagram.

D. Experimental Setup – Three-Point Beam Test

The experimental setup is shown in Figure 5.

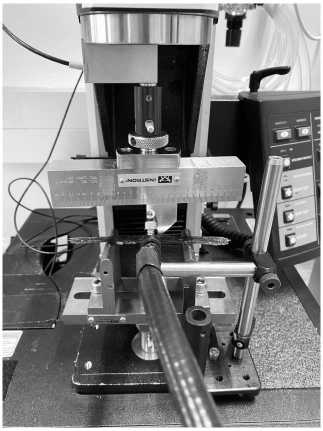

Fig. 5. Three-point beam test setup - beam and supports.

Its main component is the INSTRON© 6800 Series that enables the penetration of the sample and processes the data of the results. As a load-cell a $100\,\mathrm{N}$ load-cell from INSTRON© is used. The UV-illumination is provided by a Omnicure© S2000 with an intensity of 30 $\mathrm{W\,cm^{-2}}$. The first experiments are carried out to become accustomed to the material behavior of the composite beams (glass- and nylon fiber) with a FD of $10\,\%$, a displacement of $1.0\,\mathrm{mm}$, a velocity of $1.0\,\mathrm{mm\,min^{-1}}$, and UV-intensity of $15\,\%$. There may be small deviations in FD due to the manufacturing process. All fibers have a diameter of $0.5\,\mathrm{mm}$. For the second experiment FD of $5\,\%$, $10\,\%$, and $20\,\%$ are used with a displacement of $0.8\,\mathrm{mm}$, a velocity of $0.8\,\mathrm{mm\,min^{-1}}$ and UV-intensity of $10\,\%$. In these experiments only composite beams made of glass fibers are investigated. The UV-light is turned at a displacement of $0.4\,\mathrm{mm}$ and turned off when the displacement reaches the same displacement in the backward movement. For the experiments without UV-illumination, the whole test is deflected until $0.8\,\mathrm{mm}$ and then relaxed to its original position.

III. Results

A. Analysis of Single Fiber Pull-Out Test

The combination of both materials offers an extensive range of properties, which in some cases are desirable or must be avoided. Figure 6 shows the results of the low material conducted without UV-light and the different fibers. The experiment's results of the respective fiber are averaged in Figure 6. The difference in magnitude of $F_{\max}$ and also the difference in slope of the linear range until $F_{\max}$, which is associated with the stiffness k, is clearly visible.

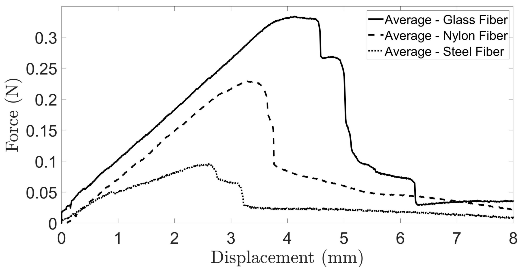

Fig. 6. Force-displacement diagram - low material - different fibers.

The highest stiffnesses can be seen with the glass and nylon fiber. These fibers have almost identical stiffnesses of $0.080\,\mathrm{N\,mm^{-1}}$ and $0.081\,\mathrm{N\,mm^{-1}}$, only $F_{\max}$ is smaller for the nylon fiber. This provides information about the strong adhesion between the low material and the glass fiber. The stiffness for the combination of the low material and steel fiber is one third smaller compared to the other fibers with $0.048\,\mathrm{N\,mm^{-1}}$. These tests are all conducted with the absence of UV-light. Interestingly, the composite materials used in these experiments can have completely different results and properties by introducing UV-light. Considerable changes of the composite material's behavior, in particular the low material with the glass fiber, can be seen in Figure 7. By exposing the exact same composite material to UV-light, drastic changes can be recognized. Starting with the dashed, gray line in Figure 7, which shows the composite material's behavior under $1\,\%$ UV-intensity, a drop of $F_{\max}$ by a factor of seven can be noticed. Also a major flattening of the slope is detected. The same trend is valid for the composite material when illuminated with an intensity of $5\,\%$ and $10\,\%$ In this case, higher intensities lead to a higher drop of $F_{\max}$ and to a decreasing trend of the slope.

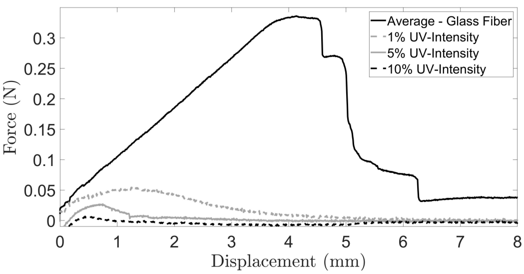

Fig. 7. Force-displacement diagram - low material - different UV-intensities.

Specifically, the change in stiffness in Figure 7 has the following values: A drop in stiffness to $0.067\,\mathrm{N\,mm^{-1}}$ is noticed under $1\,\%$, $0.063\,\mathrm{N\,mm^{-1}}$ under $5\,\%$, and $0.060\,\mathrm{N\,mm^{-1}}$ under $10\,\%$ UV-intensity. $F_{\max}$ drops from $0.340\,\mathrm{N}$ at the absence of UV-light to $0.050\,\mathrm{N}$, $0.025\,\mathrm{N}$, and $0.010\,\mathrm{N}$, respectively.

The illumination with UV-light does not necessarily mean a decrease of $F_{\max}$ and the stiffness. It can also be the case that the respective values have no decrease at all, a small decrease, or even an increase. Figure 8 and Figure 9 show these cases. Clearly to be seen are the different magnitudes of $F_{\max}$ and the various stiffnesses.

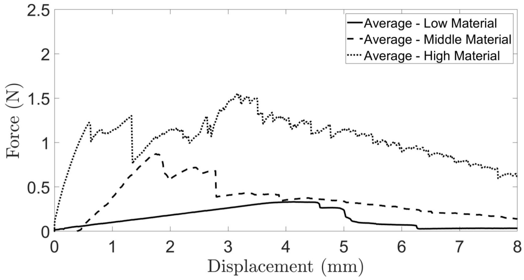

Fig. 8. Force-displacement diagram - different materials - glass fiber.

The considerable differences under UV-illumination are shown in Figure 9. This shows an increase of $F_{\max}$ from approximately $1.50\,\mathrm{N}$ to $2.50\,\mathrm{N}$ and an in stiffness from $2.77\,\mathrm{N\,mm^{-1}}$ to $2.97\,\mathrm{N\,mm^{-1}}$. A reason for an increase can be the polymerization of the composite material's chemical structure due to curing effects under UV-light. The middle material undergoes a relaxation under UV-light. The big change in stiffness from $0.75\,\mathrm{N\,mm^{-1}}$ to $0.13\,\mathrm{N\,mm^{-1}}$ is remarkable, as is the decrease of the low material in $F_{\max}$ and stiffness that tend to go towards zero.

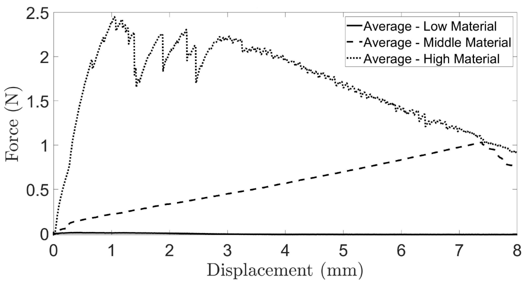

Fig. 9. Force-displacement diagram - different materials - glass fiber - UV.

An important factor to be considered in the material selection is the stiffness ratio

$$\Psi = \frac{Stiffness\, UV_{Off}}{Stiffness\, UV_{On}} \tag{2}$$

that gives a better information about the reactive behavior of the materials. By that, a heat-map is created that provides a comparison between the different values in Figure 10. The darker the rectangle in the heat-map, the bigger is the stiffness ratio and vice versa.

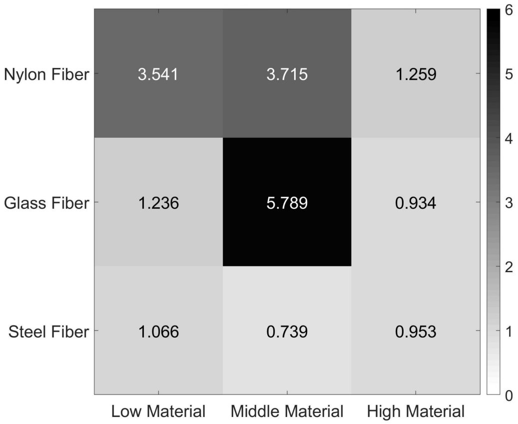

Fig. 10. Heat-map of the stiffness ratios Ψ.

The biggest ratios occur at the glass- and nylon fiber in combination with the low- and middle material. Especially the nylon fiber shows high ratio values. The glass fiber shows decent behavior with the low material and the highest ratio of all composites in combination with the middle material. With that information, a pre-material selection can be made. Therefore, one fiber and one material is eliminated from the wider selection (steel-fiber and high material). The high material becomes too brittle under UV-illumination and cannot be used as a VSD.

B. Analysis of the Three-Point Beam Test

The first tests are conducted with the nylon-reinforced beams. All of the beams have the same FD. Figure 11 shows the results for the nylon-reinforced beams with different elastomers. Starting with the middle material, the steepest slope can be seen under UV-light. It has the highest stiffness with $0.22\,\mathrm{N\,mm^{-1}}$ and the highest force of $0.22\,\mathrm{N}$. Without UV-light a stiffness of $0.19\,\mathrm{N\,mm^{-1}}$ and a force of $0.22\,\mathrm{N}$ is valid. This behavior is not desired for the VSD-prototype, which is why this material is no longer considered for the VSD-prototype. A higher stiffness can be determined with the low material for the beam without UV-light compared to the beam with UV-light. Stiffnesses of $0.08\,\mathrm{N\,mm^{-1}}$ for the non-illuminated case and $0.06\,\mathrm{N\,mm^{-1}}$ for the illuminated are valid and show the drop in stiffness.

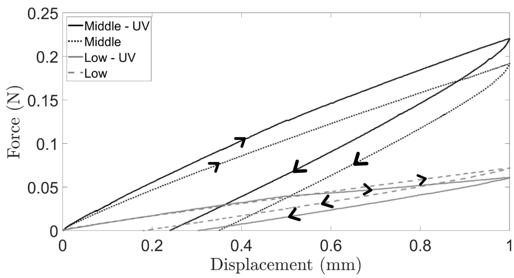

Fig. 11. Nylon fiber - overlap.

Noticeable changes can be seen with the glass-reinforced beams with significantly higher stiffnesses for both the middle- and low materials. Looking at the middle material in Figure 12, an almost identical behavior and stiffness of $4.42\,\mathrm{N\,mm^{-1}}$ without and $4.50\,\mathrm{N\,mm^{-1}}$ with UV-light can be noticed. This fact confirms that the middle material is not suitable for a VSD. Comparing the middle material to the low material, not only a smaller stiffness of $2.25\,\mathrm{N\,mm^{-1}}$ but also a change in slope and stiffness to $1.59\,\mathrm{N\,mm^{-1}}$ when illuminating the glass-reinforced beam can be noticed.

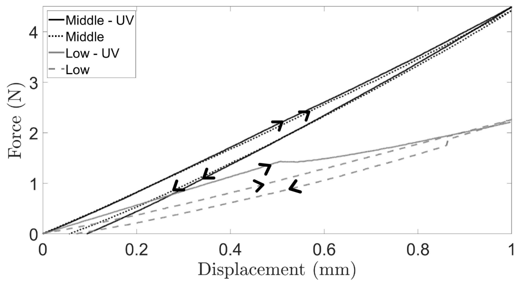

Fig. 12. Glass fiber - overlap.

By selecting the low material-glass fibers combination, six more experiments are carried out for further investigations. For these experiments the second test parameters are used. The gray areas in the bottom subplots indicate the area of UV-illumination.

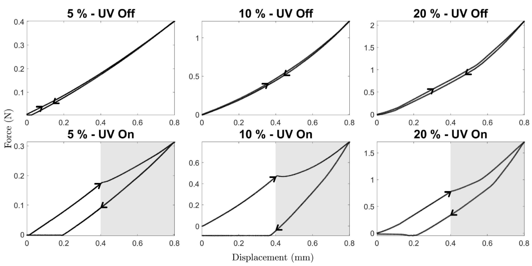

Fig. 13. Glass fiber - different densities - UV on / off.

As can be derived from Figure 13, the highest energy dissipation is in the case of the 20 % FD beam. Examining the various ratios Ψ, as well as the real performances, is now subject of the final material selection.

C. Final Material Selection

With the help of the fundamental preparations in the material selection process, a final material selection for the VSD-prototype can be made. In addition to the various results, also personal experiences are integrated into the selection process. This is the reason why the following material is chosen for the VSD-prototype: Low Material & Glass Fiber with 20 % FD. This specific composite material shows the best overall performance in terms of Δ and Ψ. This composition tends to be easy for manufacturing and does not demonstrate too sticky or fluid behavior under ambient conditions. Repetitive using of the material is possible and wear is kept low. Additionally, the force ranges are needed to withstand certain loads. Even though the comparable composites beams with different FDs show higher values of Δ and Ψ, they do not tend to be feasible for high loads.

D. Design Concept and Requirements of the Prototype

Many different possibilities for designing a VSD-prototype exist. Starting with gloves, lifting-devices, and lifting-supports, a useful application can be seen in a medical-technological device like an endoscope (Figure 14).

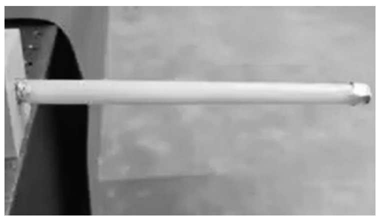

Fig. 14. VSD-prototype with transversal fibers.

It is supposed to be stiff during operational work at the desired location and soft when actuating and moving the device. Repeatability and accuracy are an essential part that must work indispensably. One of the most important requirements is the actuator's response time, which has to be in a range of 1 s. Other crucial requirements for the prototype are the high repeatability, the minimization of wear, high safety standards, and the ability to control the various movements of the actuator. For safety reasons, under no circumstances there must not be glass shattering.

IV. CONCLUSION

In the various experiments concerning the design and manufacturing process of the VSD-prototype numerous valuable data sets are found. Starting with the Single Fiber Pull-Out Tests, new insights are made by the experiments performed with this. These kind of experiments in combination with the special materials gather new findings in research along this field of materials science and soft-robotics that can be now be furthered. Referring to the findings conducted in relation to the VSD-prototype and the material selection process, promising results are found and analyzed before selecting a shortlist. Before this selection, one must mention that unknown factors exist which cannot be found by the Single Fiber Pull-Out Tests directly. Uncertainties can be the influence of polymerization under UV-illumination, the impact of UV-light in relation to the activation ability of CAN-materials, and the number of cycles the composite material can withstand before wearing out. Despite these uncertainties, the results provide solid information of the material behavior and help in the material selection process and the creation of the shortlist. The second part of experiments relates to the Three-Point Beam Tests and its final material selection for the VSD-prototype. Completely new insights in the field of the investigated composite materials are made. This experiment increases and broadens the findings conducted by the Single Fiber Pull-Out Tests due to different FDs and UV-intensities. Interesting is the change in stiffness when under UV-light, as the drops in stiffness is closer to reality in this experiment. The combination of the Single Fiber Pull-Out Tests and Three-Point Beam Tests verify the material selection process and the material selected, the low material reinforced by glass fibers. Finally, the VSD-prototype can be produced after the careful material selection. Various findings can be seen in the VSD-prototype and confirm the results and analysis of previous work. Due to problems in delivery and manufacturing, some points cannot be investigated in the way they should. A main issue is the improvisation of $PMMA$ fibers to the glass fibers in a ratio of $50/50$. Even though the characteristics are acceptable, the full potential of the optical glass fibers is not exploited. Another problem is the movement controlling of the VSD-prototype. This point is not fully investigated, as the change in stiffness is shown with the addition of weights and the resulting deformation of the beam. Still, the proof of this concept can be considered as a success as can the material selection process in total. By involving further experiments and investigations such as the influence of polymerization under UV-light or the scattering of it, further improvements can be made and the VSD-prototype may be significantly improved.

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David Altmann studies Mechatronics and Smart Technologies at Management Center Innsbruck and is currently a Visiting Research Fellow at Harvard University, John A. Paulson School of Engineering for Prof. David R. Clarke.