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Research Proposal

# Development of a Sensorized Soft Robotic Hand for Haptic Object Recognition

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# Contents



# 1 Introduction

*On the field of robotics a seed was planted and a beautiful flower is emerging, many discoveries have to be made.*

The challenge of building robots that perform well in human specific tasks such as grasping and in-hand manipulation was for a long time driven by the development of increasingly complex structures consisting of rigid elements. For some years now, a new, promising approach based on soft materials has been gathering momentum.

This research proposal consists of three parts. In the first part, an overview of the field is given, therefor the details crucial to our research are explained and the corresponding literature is referenced. In the second part, we will explain the major ideas for our research and explain their engineering and their scientific contributions. In the last part we will explain the feasibility of the project by explaining our current experience in the field as well as pointing out a detailed path for the research.

The literature part of this research proposal starts with a definition of Soft Robotics. After that, we have a short introduction to the type of materials used in soft robotics , such as different elastomers. We will then explore different actuator types by looking at their design, architecture and actuation methods. To gather an overview of soft robotic applications we discuss different use-cases of soft robots. Not all of those examples are necessarily significant to our research, but they will aid us to gather a more complete overview. The applications inspire us to have a closer look into the development of anthropomorphic hands, and we will compare soft to rigid hand designs. After pointing out the potential of soft robotic hands we concentrate on the recent progress made in the field by looking at different hand designs. We will then synthesize the knowledge from the previous sections about actuators, and combine it with the knowledge about robotic hands. Different approaches to introducing sensors into a soft robotic actuator are presented, and we pay additional attention to the challenges faced in developing such sensors. Soft hands are under-actuated and compliant:, controlling them is a difficult problem which is very relevant to the development of sensors. We will discuss these difficulties in the development of control mechanisms, and show possible solutions. In the last section, we will show recent research on perception with robotic soft grippers which will lead us in our research interests.

# 2 State of the Art - Literature

## 2.1 Definition

Until now, there has not emerged a unified definition of the term Soft Robotics, but efforts have been made to gather an overview of a dispersed field [1–4]. Soft robotics means a paradigm shift for the field of robotics. Rigid systems with limited degrees of freedom (DOFs) are replaced with rather soft structures with a theoretically infinite amount of DOFs. We consider the number of DOF as theoretically infinite because a soft robot can almost be arbitrarily deformed without being damaged. This fundamental change comes with new challenges and requires new approaches for manufacturing, sensing, and control. The term Soft Robotics often refers to the use of soft materials such as elastomers (see section 2.2). These soft materials are intrinsically soft due to their physical properties, in contrast to pliable structures, where a specific architecture leads to soft behavior [5]. It has not yet been determined whether those pliable structures can also be seen as soft robots, and thus consequently if the terms pliable and soft can be or have to be distinguished [1]. One example of such pliable structures is the Pisa Hand II. It is made of rigid elements which are connected via an elastic rubber band, which leads to pliable, adaptive behavior, despite having a mechanism consisting of mainly rigid parts [5]. Our research focuses on soft hands which are made of soft, rubber-like materials; thus softness in our terms refers to the material - rather than the compliance - of a mechanical structure. We adopt the definition of soft materials, respectively robots by Polygerinos et al. here a material is considered soft:

> when the stresses, it is subject to cause it to deform prior to damaging the class of objects for which it is designed [...]; we acknowledge that traditional robots can be thought of as soft when interacting with a harder object, such as a diamond [4].

We want to note that Salisbury had already used the term soft finger in 1982, but he did not refer to soft hands in the sense that we do. He defined a soft finger as an actuator which has a contact area with friction that is large enough to stop an object from sliding [6].We admit that it is possible to draw a connection between both definitions, but we also think that Salisbury's definition differs in too many aspects from our use of the term for usto acknowledge it as an early definition of soft robotics.

## 2.2 Materials

As explained above, soft robots are typically composed of rubber-like materials. This type of material is hyper-elastic and can elongate several hundred percent before it breaks. With this material, we are able to produce actors that use the deformation of the material under actively- and passively-applied forces, in lieu of the movement of rigid joints, to reach the goal configuration. We want to note that the term goal configuration in the context of soft robotics cannot simply refer to, for instance, a limited number of rotation angles of joints. The representation of a soft robot's configuration is, due to its almost infinite DOF, itself a challenging problem. Therefore we will discuss the representation problem in section 2.7. Soft materials are able to incorporate external influences into their configuration. This means they deform in the order of magnitude of the object their are interacting with, without taking damage. This is especially interesting since the reaction can be seen as information about the environment incorporated into the state of the actuator. In connection with a feasible-sensing technique, soft actuators have a high potential in perceptional applications.In contrast, when rigid mechanics act on the environment they change the environment's state.

Soft elastic materials can be characterized by different properties. We use the 100 % modulus which we will refer to as Young's module $E$ to characterize hyper-elastic materials in approximation with the Neo-Hooke model. For comparison, this value is sufficient, even though this model is only accurate for small deformations [7].

Some materials recently used to build soft robots are Mold Max 10 ™ ($E = 0.24\,\mathrm{MPa}$), which is for instance used for finger-shaped actuators with stretchable sensors on light basis (see section 2.6) [8]. Silicone Dragon Skin 20 ™ ($E = 0.33\,\mathrm{MPa}$) is used for the development of fiber-reinforced pneumatic fingers [9] or ELASTOSIL™ M 4601 A/B ($E = 7.0$ MPa) for the construction of a pneumatically-driven mobile robot [10].When processed, the elastomeres are in a liquid state; through a cross-linking reaction induced by a second substance, they gain their final stiffness. The cross-linking process is a chemical reaction which converts the liquid elastomer base into a solid state. Short polymer chains are linked together to create longer ones, eventually determining the physical properties of the material [11].

Two other materials we want to name are Dielectric Elastomer Actuators (DEAs) and Shape memory alloys (SMAs). Our research interest (see section 3) is focused on the improvement of soft robotics hands with fluidic soft continuum actuators (see section 2.3), where DEAs and SMAs do

not yet play an important role. For the sake of completeness and their potential in soft robotics, we will give a short comment on those material types. Initially denied by Quincke [12] but quickly contradicted by Röntgen [13], the effect of dielectric geometry change was first observed in 1880. DEAs are soft materials that change their geometry if voltage is applied [14].DEAs have already been used to build a soft gripper [15] and are a promising technology for soft robotics.
SMAs are materials that memorize a certain shape configuration to which they can recover after they have been deformed. The shape is programmed in the material by bending it into the desired shape and then heating it above a threshold temperature. After cooling down the SMA, it can be deformed. By heating it up again below the threshold temperature, it reshapes itself to its previously programmed shape [16].

## 2.3 Actuators

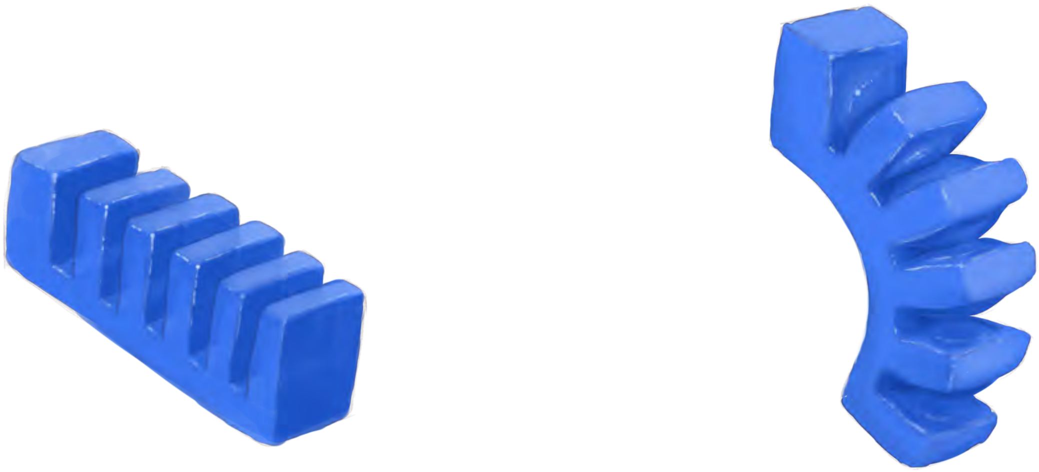
Soft robotic actuators can be grouped into different types depending on their mechanism for generating deformation. The first type we are going to analyze are fluidic soft continuum actuators actuators (FSCA) which generate a movement by "blowing up" elastomer structures. This type of actuator is actively controlled in one direction and due to its elasticity returns to its default shape when no force is applied.

**(a)** Deflated

**(b)** Inflated

**Figure 1.** The original PneuNet actuator with an elastomere layer at the bottom and the top. ©Lukas Kilian 2018

This is different from conventional actuators, where the actuator has to be controlled actively in any direction. A robotic arm, for instance, has joints which would not move if their torque is not actively controlled. One of the first types of FSCAs are the PneuNet actuators [17]. PneuNet actuators (see Figure 1) consist of several chambers along one axis in an elastomer structure. One side of the structure has thicker walls than the other, which leads to the desired behavior of controlled deformation. When the structure is inflated - thus when pressure is applied - the thin wall will expand more than the thick one, and a directed deformation of the whole structure is observable. PneuNet Actuators are built in a molding process, which makes them cheap



**(a)** Deflated **(b)** Inflated

**Figure 2.** The Fast PneuNet is an improvement of the PneuNet actuator. The upper part which is strechting part is not continous, thus is can inflate fast under lower stresses. ©Lukas Kilian 2018

and easy to produce. Thus, they can be rapidly prototyped. Zhao et al. [18] showed a way to produce PneuNet similar actuators in a scalable way by applying a method which is used in the industry for producing hollow, monolithic structures, for instance chocolate eggs. In the rotational mold-casting process, a liquid elastomer is slowly rotated in a mold until the cross-linking reaction is finished. This type of soft actuators can be thought of as one of the first rubber-based actuators and has thus played an important role in the development of other actuator types. An improved version of the actuator, called Fast-PneuNet actuator, also exists (see Figure 2). The extensible thinner wall of the actuator is replaced by spaces between the chambers. This allows the actuator to have a faster motions, smaller strains and a higher energy efficiency while bending [19].

Fiber-Reinforced Actuators FRAs are likewise hollow structures but generate their bending motion from a cord which is winded in a helix around the air-containing chamber. We can differentiate two types of Fiber-Reinforced Actuators. The first type has a axial, symmetric shape, by which we mean they are tubes with a circle-like cross-section [20]. For axial symmetrical structure type, the winding itself determines the bending direction. This implies for a symmetrical winding that the actuator does not bend but rather contracts and behaves like a McKibben-muscle actuator.

For the second type of FRA, the cross-section is not radial-symmetric [9] [21]. Such a structure generates a bending motion even if symmetrical fiber winding is used. Such a structure generates a bending motion even if symmetrical fiber-winding is used. The non-symmetic cross-section does not allow for a symmetrical distribution of forces in the pressurized finger, thus the structure is bending. Another way to enforce a specific bending direction is to introduce a fiber fabric into the neural plane of the actuator which hinders one side of the actuator from extending and thus leads to the desired motion [22] [8]. Those two approaches of fiber-reinforcing can also be combined in order to guide more force into the bending motion and less into the deformation of the the neutral plane of the finger [23] [21].

A third architecture are STIFF-FLOP actuators [24]. They consist of a symmetric tube-like structure with a circular cross-section. In the middle of the cross section is a stiffening channel which is based on the jamming granular principle [25] surrounded by three air chambers at twelve, four, and eight o'clock. This design allows the actuator to bend in any direction by superposition of the bending directions achieved by each of the three air chambers individually. If a desired deformation is reached, the stiffening channel is used to fix the actuator in that specific configuration.
We have mentioned three important types of FSCAs, because we think that they are the most relevant to our research even though there are many more types such as compositions of McKibben muscles [26].

## 2.4 Use Cases of Soft Robots

One of the reasons for the increasing popularity of soft robotics is unquestionably its many potential applications (for a extensive overview we recommend [2], [4]). We will provide an overview over the range of applications and focus on the applications specific to our research. Shepard et al. [27] applied FSCAs for locomotion. They used PneuNet-like actuators to built a completely soft quadruple robot which is able to displace itself. For its walk it uses different crawling movement modes which are either designed for fast displacement or for undergoing short gaps. Due to its softness, the robot is especially robust against external forces and can, for instance, deflate itself before an impact occurs. Equipped with a dashboard camera, the robot is able to explore flat passages and might be used for search and rescue application in unstable rubble [10].

Another application of FSCAs in locomotion is under water robot, such as the autonomous fish [28]. It uses pneumatic cells in its tail fin to produce a rapid motion which is used to displace the fish underwater. In the front-part corpus it contains a pressure tank and all the electronics needed to control the robot. After further development, it could be used as a tool for maritime research. Both applications show that soft robots also have potential to play a role in mobile robotics in the future.

In automation, robots play a major role, but the environments in which robots work are heavily engineered. The major reason for that is that engineering a control which is able to react and adapt to every eventuality is very hard and changing the environment is comparably easy. Environments which cannot be engineered therefore present a particularly difficult challenge for robots. One example of such an environments is a field for vegetables or fruits . Here a soft robotic gripper could be an option for the harvest of sensitive fruits.

Their softness might allow them to collect fruit from trees without giving them pressure marks. It is of note that the Harvard University spin off *Soft Robotics, Inc.* developed a type of pneumatic soft-gripper which is marketable. This gripper is based on the Fast PneuNet architecture and can be used to grip sensitive object such as fruits. Humans have to interact with their environment uncountable times a day: many of those integrations are grasping motions and manipulations of objects in our hands to make them usable. A pen, for instance, is almost useless after picking it up from a table. Only after an elegant rotation in the hand does it becomes functional. Consequently, grasping and in-hand manipulations have always been an interests in robotics. The development of hands with a performance which is comparable to human performance has mainly been based on rigid structures, and only recently have soft materials came into the focus of the roboticist (see section 2.5).

One important application of robotic soft hands or soft hand like structures such as gloves are orthosis. After accidents or diseases a patient may loose the ability to control their hands in a functional manner. Losing the hand functionality means a huge loss in life quality. Soft robotic support devices might help to partly restore the hands functionality. A glove made from rubber using PneuNet like actuators is used to support the human hand while grasping [29]. The glove has curvature sensing and is able to be controlled via Electromyography (EMG) signals. PneuNet actuators are located at at the back of his hand and inflate as soon as the patients wants to grab something, leading to a bending of the actuators which support the grasp.
A further medical application of soft robotic gloves is in rehabilitation. Takahashi et.al [30] suggest that the rehabilitation results of patients using robotic glove assistance are significantly better than those of the ones without support. Such an assistance glove was developed by Polygerinos et al. and consists of PneuNet actuators which are woven into a textile glove. The whole device can be adapted to the patient's hand size [31] [32]. In the use the therapist controls the actuation and helps the patient to regain its grasping power and dexterity.

If a human loses his hand completely, he needs a prosthesis. Soft hands might be an option for the replacement of a hand, since their intrinsic softness makes them safe for robot- human interaction.
This application is still experimental since FCSA-based actuators rely on pressurized air and valves. The level of integration is not yet high enough for this application.

## 2.5 Anthropomorphic Hands

In this chapter, we will study different concepts of rigid and soft anthropomorphic hands and discuss criteria for their development goals. Then we will study different soft hand architectures and their abilities, which we can use to benchmark our research.
Many approaches of building a anthropomorphic hand have been of a rigid nature [33] [34] [35].

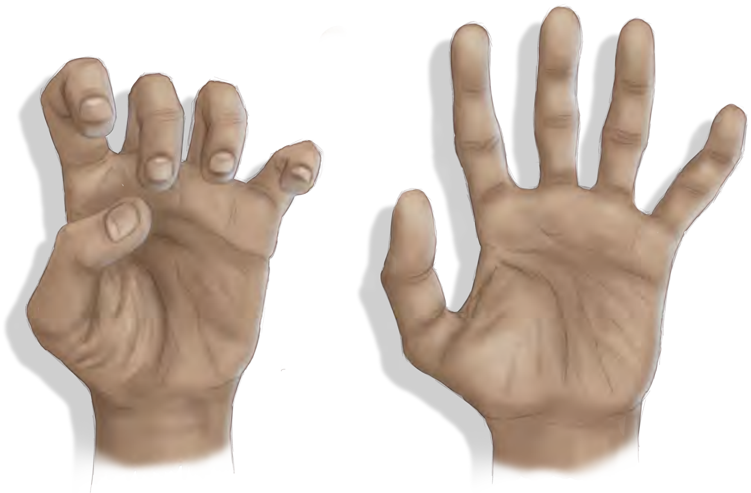


**Figure 3.** The term anthropomorph refers to the object which are human like shaped. Our proposed hand will be inspired by the human. A key feature of the human hand is the capability of positioning its thumb on the opposite side of the palm (left). ©Lukas Kilian 2018

Anthropomorphic hands are inspired by the humand counterpart and thus inherit imporant features such as the opposable thumb (see Figure 3). A famous example of an early anthropomorphic hand is the MIT Utah hand [36]. The MIT Utah hand is inspired by its human counterpart, it has three fingers, one opposed thumb, and a completely rigid palm which has no degrees of freedom.

Its finger and thumbs are actuated via tendons which are fixed at pneumatic cylinders to operate them. The hand is capable of performing in-hand manipulations and grasping procedures. Its developers had in mind the idea of creating a *high performance research tool for the study of machine dexterity*. They define five criteria, some of which we want to reinterpret in the context of soft robotics [36]. This can be useful for our research, since we think a soft robotic hand has to be designed as a whole and not just as an ensemble of soft actuators.

The first criteria is that the hand has *many degrees of freedom* which, in the context of rigid hand, implies controllable degrees of freedom.

The direct control over the DOFs is critical to rigid hands, because they have only low or no compliance which can be exploited. Soft materials, in contrast, have compliance as their key feature, almost all degrees of freedom are uncontrollable. They are usually heavily under-actuated and their compliance is their major advantage as well as disadvantage compared to rigid hands. We can analyze the compliance, and thus the deformations, via so-called morphological computations [37]. These computations can be seen as the passive behaviors of actuators that follow directly from their morphology. A soft hand made of PneuFlex actuators, for instance, adapts while grasping passively to the shape of an object [23] and thus performs a morphological computation. *Very high active and passive performance* are reasonably separated features for rigid hand but for a hand made from soft materials this distinction is blurred. As described previously, the active and the passive performance are closely related through morphological computations and thus both performances have to be evaluated at the same time. Ghazi Zahedi et al.suggest that the morphological computation should be evaluated by choosing a hand with allows for high versatility and simple control, which makes it easier to identify those deformations which are good and those which are bad for reaching the desired goal [38]. *The capability to serve as a vehicle for studying a broad variety of tactile sensing systems*is a feature which is hard to implement on soft robotic hands since their morphology does not allow usto simply attach sensors. The actuation of PneuNet or other FCSA architectures are based on different levels of expansions in different parts of the actuator. This means our sensor have to deal with the expansion, which makes designing them challenging. One solution is to allow them to expand based on their key feature, and design them as stretch sensors. Different designs have been proposed: for instance, sensors can be built into the finger [8] or can be connected to them externally for instance via glue [39] (see section 2.6).

Another hand we want to have a look at is the Pisa/IIT SoftHand [5]. We can consider it as soft only undera definition where pliable, rigid structures are included. Yet we think it is important to study, because of its profound theoretical framework, which was determining for its design. The design is based on the concept of soft synergies and adaptive synergies. Soft synergies can be described as a reference hand configuration which a hand tries to reach if a certain object is grasped. If an object hinders the hand fromreaching soft synergy, the geometrical constraints, in combination with its compliance, demands that the hand adapt to a different configuration or synergy [40]. We want to note that the construction of a hand which can follow the soft-synergies strategy requires fingers that can be position-controlled.

The second term necessary to understand the design principle of the Pisa/IIT SoftHand is adaptive synergy. If a hand is force-controlled in the sense that a controller applies a specific force to a prime mover which distributes the force over a differential to secondary movers, then the final synergy of the hand grasping an object is called adaptive synergy. The Pisa/IIT is designed in a way that it is force-controlled by only one motor but the hand reacts on objects as it would follow a soft-synergy strategy. This means the hand adapts to the shape of an object like it would have a reference soft synergy, but it is its mechanical design by which it is able to adapt to that shape. For the hands design small rigid elements have been used that are connected via flexible tendons. The elasticity of the tendons as well as the configuration of the pulls in the fingers allow for further pliability of the hand.

Different approaches have been tried to make use of the intrinsic softness to create a gripper: some of them are anthropomorphic [9] [23], some are not anthropomorphic [17] [41] [42]. Since we are interested in anthropomorphic hand design, we will have a closer look at the modular RBO Hand 2 [23]. It consists of PneuFlex Actuators which are molded using a elastomer with $E = 70 - 300\,\mathrm{kPa}$ and elongation at break between 400% and 500%. After molding, they are supported by a winding, with nylon strings and a tissue in the bottom to create a neutral plane which cannot expand. The hand's palm and thumb also consist of PneuFlex actuators: this architecture enables the hand to oppose the thumb, and allows for the possibility of performing in-hand manipulations. Its actuators are mounted on a 3D-printed scaffold which can be thought of as the back of a hand. It was shown that the hand has a high postural diversity, reaching 31 of 33 grasps in the Feix taxonomy [43]. Furthermore, it has been shown that the hand is capable of robust grasping of different object shapes, even under external disturbances [23]. Its compliance helps to create the robustness and dexterity described above, but this also leads to problems. One of the issues is the reproducibility of grasp when an object is placed in the hand. Due to the geometrical constraints introduced by the object, the final hand postures vary substantially. Even if this can be seen as an advantage which makes grasping more robust, it may also introduce difficulties when performing dexterous in-hand manipulations. There are of courseother hands on which we have decided not to focus, because we think the above named hands are the most relevant to our research.

## 2.6 Sensory

Sensing is a core skill of any human hand and it is fully integrated. As impressive as that is, as hard is it to create something similar for robotic hands. The previously-described elasticity and functional principle of soft actuators introduce various challenges for their sensing . We focus on the sensing of FCSAs. The elastomer used in FCSAs often expands over 200% if the actuator is fully inflated. A conventional sensor cannot cope with the expansion and is therefore not suitable. Different approaches on the basis of Gallium-Indium Alloy have been developed to measure the curvature of a FCSA and we will present two of them [42], [39]. Furthermore, we will present two methods based on optical waveguides [8] [44] and one based on sound waves [45].

Eutectic gallium indium Alloy (eGaIn) is liquid at room temperature and it is used to build stretchable sensors [46]. Those sensors are made up of a thin elastomer layer which is equipped with eGaIn channels that can be as small as $25\mu$m. The channels are conductive and their resistance depends on the channels diameter.

If pressure is applied to the elastomer layer the channels diameter are locally reduced hence the resistance increases temporarily until the pressure is released. The same effect is observed if the layer is elongated this makes this type of sensor applicable as a strain sensor [46]

A similar method is applied directly to soft actuators. The eGaIn alloy is directly injected in a channel at the back surface of a soft actuator [42]. Since the back surface is opposite to the neutral plane the sensor layer experiences maximal strain.

Another method in to glue strain sensors, similar to the previously described, to different sides of a soft actuator. It is shown that with a well layouted ensemble of eGaIn strain sensors on a soft finger, it is possible to find a mapping between the data coming the sensors and a three dimensional configuration describing the bending of the soft actuator [39]. Such a representation of the finger configuration can be advantageous over the pure sensor data because of different reasons. At first it easy interpretable for humans thus motions and deformations can be studied directly and secondly such a representation can be used to have a hand independent way to represent hand synergies.

Another approach is to use the air chamber within a FSCA as a resonance space, place a microphone into the finger and record the sound when the finger is touching an object [45]. The microphone is placed as an IC into the base of a PneuFlex finger so that it does not affect the compliance of the actuator. Sound is recorded while the finger has contact with an acrylic stip at different finger locations (e.g.tip, base). The recording is used to classify the contact locations on the finger. For a given test set the predictions are significantly better than a random guess. This article shows the potential of sound sensors in soft actuators which leaves a lot of space for further investigation.

Light might be another option for sensing soft actuators and we present two different ways to implement a light based sensing. The first method is based on normal plastic optical fibers POF which are used for instance in data transmission applications. Kuang has shown that bending and stretching of POFs increases the light intensity loss through the fiber [47]. This suggests that optical plastic fibers can be used as bending sensors for soft actuators. This suggests that optical plastic fibers can be used as bending sensors for soft actuators. Zhao et al. [44] were able to use such an optical fiber for curvature control in an soft glove previously described (see section 2.4). In the base of the finger a LED and a photo diode is placed each at one end of the POF passing in an U-shape through the tip of the finger. To increase the loss during bending they roughened one side of the POC with a laser. A polynomial fit between the loss and the curvature $\frac{1}{\kappa} = r$ is then used to design a closed loop curvature control for the glove's fingers.

One major problem in using POFs is that they are not stretchable, thus they are not suitable as strain sensors in soft hands. To overcome the problem of the POFs, stretchable optical sensors have been development but could only produced with high efforts [48].But recently a new method was developed which makes it possible to produce a cheap elastomer based wave guide which are capable of elongation [8]. This type of waveguide underlies the same functional principle as the POF but is made of different materials which have a smaller elastic module and a higher elongation at break. Three of those waveguides are used in the inside of a FSCA in order to predict the deformation of the actuator.

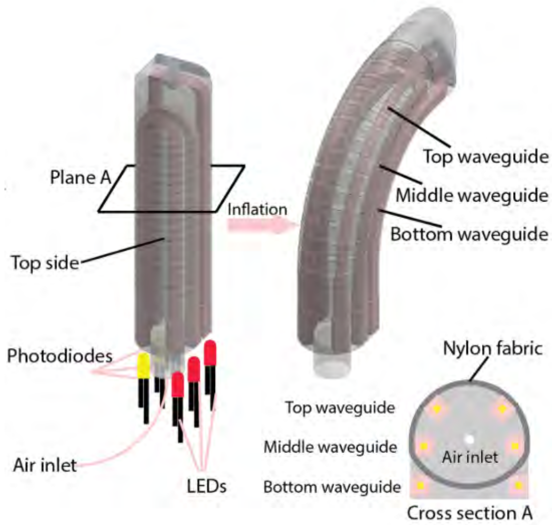



**Figure 4.** The strechtable optical waveguides are placed in the finger in order to measere the fingers Deformation. A LED is placed on one end of the waveguide and a photodetector at the other. Used with kindly permission of Huichan Zhao.

The waveguides are located close to the surface of the actuators so they react on pressure and can possibly be used for tactile sensing as well.

Lastly we want to note that the pressure within the air chambers can be easily be measured by installing for instance a differential pressure sensor parallel to the air chambers of the FSCAs. This information can be used as an addition to stretchable sensors in order to predict the deformation of a soft actuator [39].

Sensors are the base for closed loop control and their quality and accuracy determines the quality of the control. In the next section we will focus on the control soft robots.

## 2.7 Control

The control of soft robots turns out to be tough problem, but we will focus in this chapter again on FSCAs since they are the type of actuator we are planning to use throughout this research project. We will describe several problems for the control of FSCAs which are related to their softness in more detail before we address different approaches for soft robotic control. As we described previously, FSCAs are made of soft materials which makes them are highly under-actuated. Assuming a specific pneumatic soft actuator, its configuration depends on the amount of air in its chambers and the external forces applied to it. The external forces can be, for instance, induced by an object which it tries to grasp or an obstacle it is colliding with. Without external forces and in a static situation, the mapping between the air in the actuator chambers and its configuration might be uniquely defined. But even for small external forces, the mapping is not injective anymore. The amount of reachable configurations of the actuators under applied external forces is almost infinite, but the amount of actively-controlled variables is limited to a few binary valves. This brings up the question if the compliance of the hand described in section 2.5 is an advantage which makes control simpler, or if it is rather a disadvantage which makes the control unnecessarily hard. The force which eventually bends the actuator actively is usually defined by the air within the chambers of the finger, but not in all cases we want only to control the bending or curvature of the fingers. Hence if we talk about control we should first defined which our control variable is which turns out to be not trivial for soft actuators. The control variable typically depends on the application, examples are in the context of the previously described FCSAs the curvature of the finger or also the position of an end-effector on a soft parallel robot [49].One approach is to use the air mass in the finger rather than curvature or force as the control variable, this can be done by using a model of the air flow and predicting the current air mass in the finger from the opening time of the valves [50]. Another approach is to control the position of an end-effector of a cable driven parallel soft robot [49]. The position control is done with a real time FEM Simulation of the soft robot structure. The control takes a desired position of the end-effector as in input and calculates the corresponding forces which have to be applied by the servo driven cables in order to reach the desired position. This type of control requires a sophisticated model of the actuator as well as enough controllable degrees of freedom.

Both previously mentioned control techniques fall under open loop control where no knowledge about the actual state of the system is available. For open-loop control we have no knowledge about the actual state configuration of the actuator and consequently we need a precise model of our system which in the case of soft robots is fairly hard.

Closed loop as a strategy relies on the capability to gather information about the actual state of the actuator or more general the state of the system. If information about the state of our system is available control techniques such as PID position control are possible. For the PID control a given desired curvature is fed into the controller. Oversimplified one could explain the PID control in the following sense, the PID-controller compares the current curvature to the desired curvature and inflates the the actuator until the desired curvature is reached. One possibility to gather the information about the curvature is externally with a camera [51]. Since this requires a comprehensive experimental setup, it is not feasible for a possible application. To reach a higher portability of soft robots, internal sensor are used. In order to use of the raw data coming from a sensor for control a connection to the control variable is needed. One possible connection previously described is realized via a function fit between the electrical resistance coming from a liquid metal strain sensor and the deformation of a PneuFlex soft finger in three dimensions [39]. The same technique can also be applied to the POF sensors. The actuator is bending and the engraved cracks in the fiber are closing, this means the light intensity at the receiving end of the fiber is increasing. The intensity change can be measured and the curvature can be deducted as described above [44].

All of the above described controls try to control a single variable rather than the complete soft robot. The problem of controlling a soft structure under applied external forces or loads is a challenging one which until now has no satisfying solution. The interaction with any object causes huge disturbances to the soft actuator and are hardly predicable. They should be considered as a feature of control and have to be included thoroughly.

## 2.8 Haptic Perception

Hapic perception compared to our visual or acoustical perception is able to perform interactive perception. For a hand it is possible to manipulate the object which it is trying to classify. The visual system provides accurate spatial information whereas haptic perception gives information about the shape or the structure of an object [52]. Perception plays also an important role for robots. It is the ability to interpret the incoming sensor data so that we can gather information about the environment. In this section we will focus of the haptic perception of robots, which is an important base for the interaction with its surrounding.

A soft gripper, as previously described, has great potential for haptic perception. This was shown with a non-anthropomorphic soft gripper consisting of three PneuNet actuators [53]. The soft gripper fingers are equipped with commercial bending sensors in the neutral plane of the fingers. The bending for each finger while grasping an object is the input data on which the classifier is trained. Here a k-nearest neighbor approach is chosen, but others are also possible. An improvement of this method was done via a proprioceptive grasp technique. Here it is not the raw values, but rather the configuration of the fingers that are used to identify an object [54]. For this a model has to be developed in order to connect the sensor data to the finger configuration. In this set-up the curvature of the PneuFlex Actuator is the representation of configuration. The model thus consists of a function fit between the data coming from the sensor and the actual curvature of the actuator.

# 3 Research Interests

## 3.1 Goals

In this master's thesis, we want to investigate new perception and control possibilities for FSCA-based sensor-equipped soft robots. In particular, we want to focus on soft anthropomorphic hands and their capabilities. We propose a Soft Robotic Hand which is capable of performing object recognition based on its deformations. Therefor we will approach the problem from two different sides. At first we want to develop an architecture for the soft robotic hand and address the key features that a hand has to have in order to perform well in a humanoid environment. This means we want to build a soft hand which is able to oppose its thumb in order to perform grasping and in-hand manipulations. After we decided on a design and build a prototype, we will introduce sensors into our hand, those are the basis for our perception and later the feedback control. We are planning to use the elastic waveguide sensors developed by Zhao et al. in the hand as well as in the palm [8]. Throughout this process we are planning to use the SOFA simulator to test different hand designs before cast molding them, as well as to find positions for our sensors within the soft hand. The hand will consist FCSA fingers and most likely a FCSA palm. We think a FCSA palm is beneficial for a soft hand, because it allows the palm to adapt to objects in grasping task, as well as it allows better control for the thumb which is needed in manipulation tasks. We want to equip both the palm and the fingers which the previously named sensors.

The second part of the project will focus on the algorithmic side of our control and perception. After the hand is finished and equipped with sensors we want to perform an object recognition task in order to show the perceptional capabilities of our design. The object recognition task can be described as a classification problem based on the sensor data which is recorded when an object is grasped. The objects in our set, vary in their geometrical (e.g. cube, sphere) as well as their material properties (e.g. soft, hard). Due to the intrinsic compliance we assume that soft structures are naturally superior for perception tasks. We want to measure the adaptation of the soft hand to our objects thus its deformations. We expect each object to have an unique signature of deformations, if our sensors are capable of measuring those, we should be able to classify the objects. Therefor we are planning to try different Machine Learning approaches. One path for the classification would be to grasp different object with one specific desired hand configuration. The desired position can for instance be a set of desired pressures in the hand or the desired air mass in the hand. After reaching the desired configuration we record the deformations measured by the sensors. Those deformations will be the data $X$ and the object will be our classes $y$. After the data is captured we will decide for a specific classification method.

The development of a hand which is capable of object recognition raises the chance of studying the minimal requirements for in-hand perception itself. We see the human hand with its performance as the ultimate benchmark and we think we can learn important lessons from its

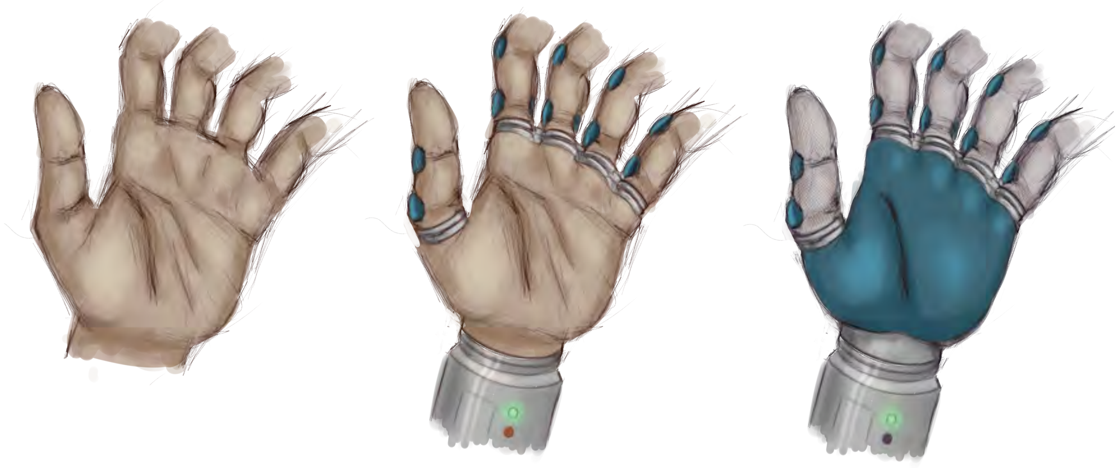


**Figure 5.** The inspiration of our hand is taken by the human hand. We Propose a hand which is entirely soft, thus adapts well to the object it is interacting with. ©Lukas Kilian 2018

perception behavior (see Figure 5). Throughout our studies, we want to answer the question in how far it is possible to recognize objects by only using a anthropomorphic hand. Therefore we are planning to do the same object recognition experiment with a human with reduced sensing capabilities. We are are planning to remove the vision by blind folding and reduction of touch sensing by wearing gloves. Depending on the strategy the human is using to recognize object we are want to adapt our recognition procedure.

In order to deploy different types of hardware and software fast and efficiently we build a so called ValveBox. The ValveBox will be an integrated control device for pneumatically driven soft robots. It consists of a Raspberry PI as the central control unit and a solenoid valve manifold together with the corresponding pressure sensors. It will run a ROS server which controls the valves as well as it reads out the pressure sensors and will be controllable via network from a remote Laptop also running ROS. To sum our proposal up we think our **engineering contributions** in the master thesis will be

- the development of a integrated control device for FSCA control, which makes fast deployment of pneumatic actuated possible.
- the design and construction of a soft robotic hand equipped with sensors to measure deformation.
- the application of a Machine Learning algorithm to object recognition of a soft hand.

and our **scientific contributions** will be

- to gain an understanding for the minimal requirements of vision-less objection recognition.
- to show the capabilities of soft materials for perception tasks.
- to show the capabilities of wave guide sensors for perception tasks.

## 3.2 Feasibility and Schedule

In this chapter we will quickly explain the feasibility of the proposed master thesis. Our proposal is mainly based on the experience gained in the development of a feedback curvature control for the RBO hand 2 (see attachment). In that project we explored the capabilities of a newly developed liquid metal strain sensor for the PneuFlex Actuators [39]. By using the strain sensors it is possible to measure the deformation of the finger in different directions. To show the capabilities of such sensors we developed a closed-loop curvature control. In a condensed description our control works as following: The air mass in the finger is increased until our specified goal curvature is reached.

Since the previously described project focuses on the capabilities of soft hands for control, this master thesis will focus on the perception capabilities of soft hands. To show that the proposed research project is achievable in the give time frame we appended a detailed schedule for the next year.

**Figure 6.** Schedule for Master Thesis I: Hardware Focused Period

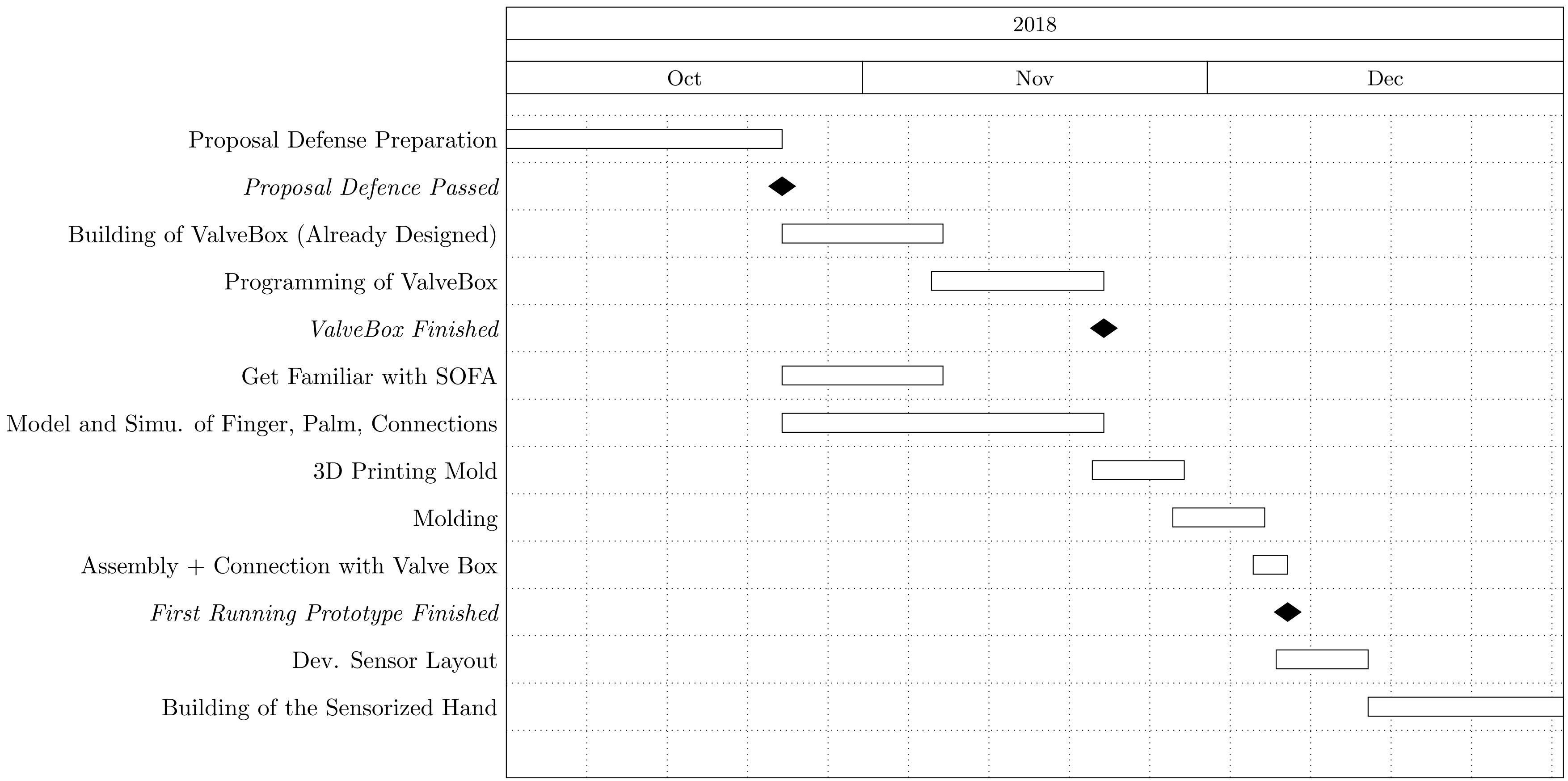
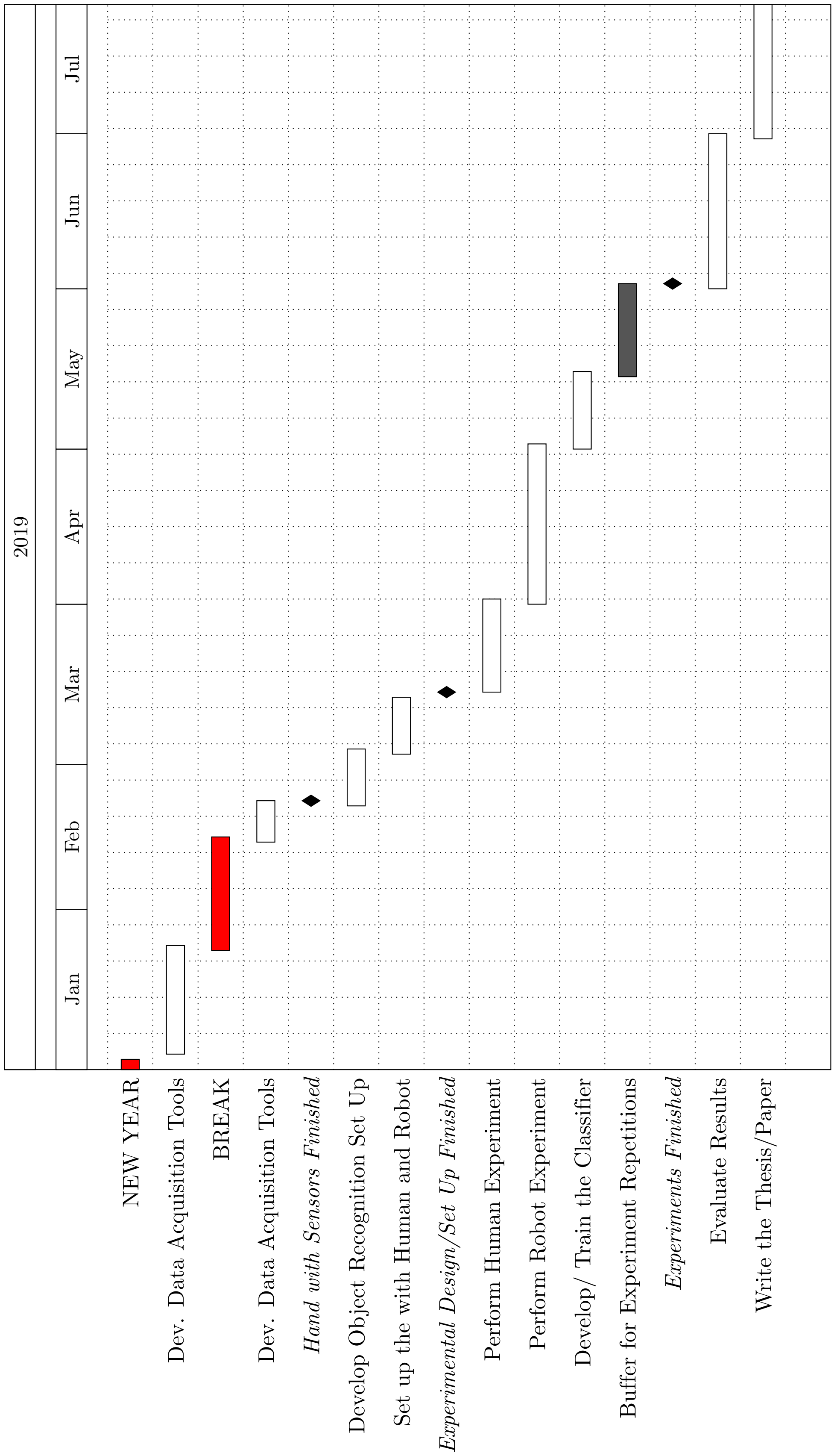


**Figure 7.** Schedule for Master Thesis I: Software Focused Period



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