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Proseminar Informatics in Medicine

Smart Medical Phantoms
State Of The Art In Construction And Usage Of Robotic And Sensory Equipment

Proseminar work of

Philipp Seidel

At the KIT Department of Informatics
Institute for Anthropomatics and Robotics (IAR) -
Health Robotics and Automation (HERA)

Reviewer: Jun.-Prof. Dr. Franziska Mathis-Ullrich
Advisor: Christian Marzi, M.Sc.

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Abstract

This work will provide an overview of the current state of the art in smart phantom construction. In addition to this multiple examples of recently employed smart phantoms will be presented showing the robotics and sensory equipment that were implemented in them. This will be achieved in three parts. The first part focuses on materials that are used in modern phantom construction. The next part focuses on the methods used to shape said materials into the desired phantoms. The third and last part then explores multiple examples of phantoms utilizing both the materials and methods introduced before in order to give an insight into the possibilities arising from them.

Contents

1 Introduction

Medical phantoms have been in usage as a vital part of scientific research for many years. Especially in research concerning robotic surgery, as well as radiation driven condition analysis, phantoms have recently become a mayor contributor to scientific progress. In recent years new ways of manufacturing, such as 3D-printing, have become available and have greatly reduced the costs of phantoms while simultaneously enabling more complex structures. At the same time phantoms have progressively been fitted with robotic equipment, increasing the amount of information gathered from them both by providing researchers with sensory data as well as by simulating the behaviour of real life specimen much more accurately. These so called 'smart phantoms' have been used in training physicians, providing both real time feedback as well as a more realistic interface compared to non-smart phantoms.

In this report I will present the current state of the art in construction of 'smart phantoms'. In doing so I will give an overview over materials used in phantom construction, manufacturing techniques and possibilities that arise from them. I will then present multiple examples of recently constructed 'smart phantoms', employing either sensory systems or robotics.

2 Materials used in medical phantom manufacturing

Phantoms, both of the smart and non-smart kind, find usage in a wide range of applications. These differ in both what is to be replicated as well as in the techniques used to measure the phantoms properties. For example one phantom could be used to determine the accuracy of a radiation driven imaging device such as a MRT on a full human thorax while another could be used to test a new kind of robotic catheter steering system in a simplified blood vessel. These applications are obviously quite different in both goal and desired phantom complexity. Depending on the application as well as on the material that is to be simulated different materials are used in manufacturing phantoms. Some materials will only be worth considering when working with ultrasound while others need to have mechanical properties similar to their real life counter parts. Materials with realistic mechanical properties are often found in medical phantoms, designed to aid the development of surgical robots or to train physicians. In such applications silicon rubber will often be used to simulate muscles or blood vessels as it provides similar flexibility and is relatively cheap. As silicon tubes are commercially available it will often be the material of choice when it comes to the simulation of blood vessels. A good example of this is a study performed at the Toyo University in October of 2020 experimenting with an artificial beating blood vessel model [1]. The experimental setup of this study can be seen in figure 1, the silicon tube vessel phantom highlighted in the front.

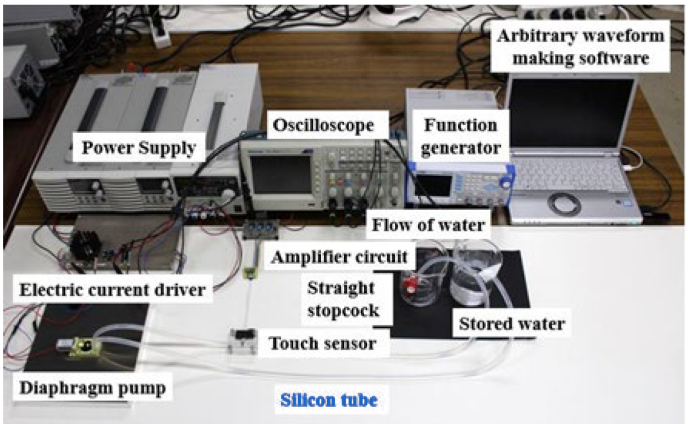

Figure 1: Usage of silicon tube in the artificial beating blood vessel model [1]

Even tough silicon tube is cheap it does not provide a great amount of realism as real blood vessels often have shapes that are much more complex. Other Materials used to simulate blood vessels have also been explored. The table shown in figure 2 represents an overview of physical parameters of the materials considered by researchers at the Tokyo University of Agriculture and Technology [2]. As the researchers were experimenting with ultrasound responsivity of their respective phantoms the acoustic impedance and sound speed of the used materials became information worth considering.

It is worth mentioning, that urethane and the silicon rubber listed are liquid at room temperature and thus need a casting mold to be brought into the correct shape while the other materials can be 3D-printed directly [2].

Selected silicon-based polymers also distinguish themselves by having a fast curing time, their stability at room temperature and their long shelf life [3]. A specific example of such a polymer is 'Dragon Skin®'(Dragon Skin 30, Smooth-On, Macungie, PA, USA, q = 1.08 g/cm³) which was used by researchers at the VU University Medical Center Amsterdam in 2018 to produce the soft tissue of a life-sized human thorax phantom [3] another is TangoPlus [4]. Silicon-based polymers also come with the advantage of having both a similar radio density as well as similar mechanical properties when compared to human tissue.

Materials	Weight density [g/cm^3]	Sound speed [m/s]	Acoustic impedance [10^6kg/m^{2}s]
Natural rubber (N)	0.92	1500	1.37
Urethane (U)	1.04	1507	1.57
Silicon rubber (S)	1.17	985	1.15
UV-curable silicon rubber (UVS)	1.03	1170	1.21
Rubber-like resin (RLR)	1.12	1805	2.02
Flexible resin (FR)	1.13	1713	1.94
Blood vessel	1.07	1600	1.7

Figure 2: Materials considered by the researchers at Tokyo University with their respective properties [2]

Other materials used to simulate human tissue include Nylon, due to it being 3D-printable at high resolution while providing somewhat similar density [3], as well as Agar [2] and Plastisol [5] due to their density, which is similar to human tissue.

In order to produce bone-like structures the material of choice will often be Gypsum as it can be 3D-printed while providing similar radio-density to human bone as well as somewhat similar mechanical properties.

In figure 3 the bone-like structures made of 3D-printed Gypsum, the tissue produced by 3D-printing Nylon and the soft tissue made of silicon-based polymer used by the study mentioned above can be seen [3].

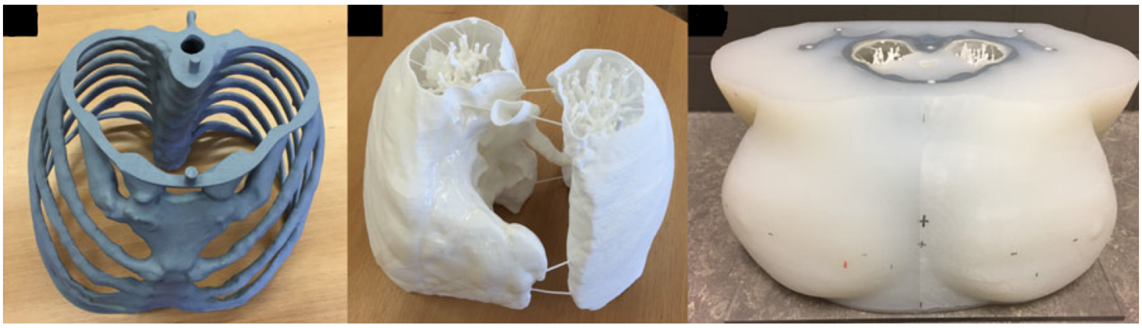

Figure 3: left: bone-like structure made of Gypsum, middle: Tissue made of Nylon, right: Tissue and bone-like structures embedded into soft tissue made of silicon-based polymer [3]

As electronics have increasingly been incorporated into many phantoms, the need for soft sensors has become apparent. A material used as a soft sensory component has been Conductive Thermoplastic Elastomer or CTPE for short [6]. CTPE offeres a high tensile resistance while being flexible as well as conductive. CTPE can be produced in many shapes thus offering versatility in the number of possible use cases. Its resistance also has a linear response to strain which enables its use as a tactile sensor.

3 Methods used in medical phantom manufacturing

With technological advancements in industrial manufacturing have come new and exciting methods used in medical phantom construction. The most prominent method that has come from recent manufacturing development has been the technology of 3D-printing. Many researchers have since utilized 3D-printing to create structures previously unachievable. While 3D-printing creates exciting possibilities, the older, more traditional methods of manufacture are still widely used. Often these methods are used in junction with 3D-printing to produce phantoms benefiting from both.

A good example of 3D-printing technologies being applied in junction with traditional methods is the previously mentioned study which sought out to construct a female thorax phantom for medical imaging purposes [3]. The researchers 3D-printed parts of their phantom using both Nylon as well as gypsum while casting a third part out of a silicon-based polymer. The mold used for casting was also 3D-printed. The researchers hired a commercial 3D-printing company to print the parts and then assembled the phantom themselves. The casting of the silicon-based outer shell was performed by the researchers.

Casting is a method traditionally used in many industries. It is thus also frequently found in phantom construction as well as other prototype construction. Such as described in a paper, published by the DGIST-ETH Microrobotics Research Center in 2018, concerning a study in course of which a micro robot was constructed using a silicon elastomer mixture [7]. Casting silicon or other materials has some advantages over 3D-printing but lacks behind in other regards. Casting may often be cheaper, result in more uniform material density and is easier to execute while 3D-printing gives access to new materials and provides the ability to plan ahead digitally. 3D-printing also gives way to more complex structures as no mold needs to be removed in the construction process which could damage fragile structures.

Depending on the material that is to be printed as well as on the desired print quality, different kinds of 3D-printers may be used. When planning to print bone-like structures out of gypsum an inkjet printer using binder jetting is a good option as it allows for Gypsium powder to be used as print material. Printing the periphery in solidly while filling inner parts with infill material will result in "ideally mimicked bony structures" [3, p. 3]. When printing Nylon, selective laser sintering 3D-printers are the machines of choice while UV-curable silicon, being liquid, can only be 3D-printed using stereo lithography printers. As different 3D-printers are required in order to print multi material phantoms, commercial 3D-printing companies are often hired to save cost.

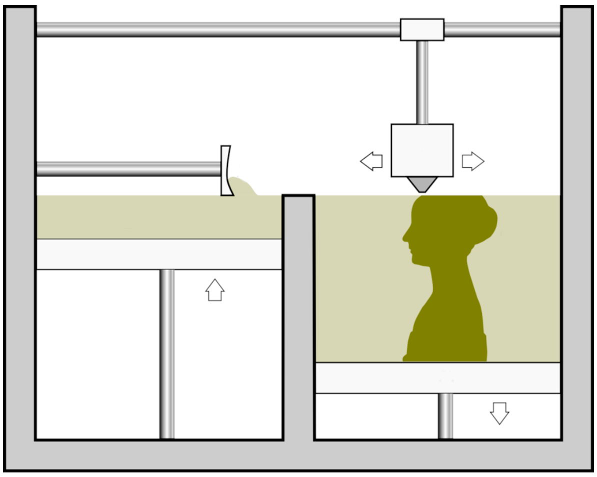

Figure 4: Schematic of a binder jetter 3D-printer [?]

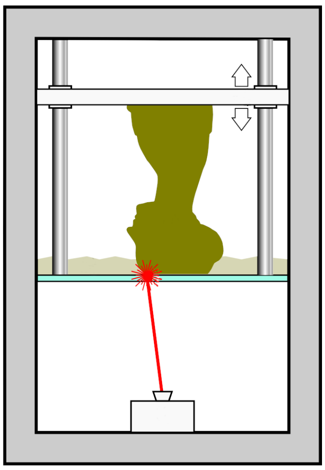

Figure 5: Schematic of a stereo lithography 3D-printer [?]

Because demand for vascular phantoms has been increasing, dedicated companies, such as Elastrat (Geneva, Switzerland), have been created which specialize in the production of vascular phantoms. A good example of researchers employing a commercially sold vascular phantom is an experiment documented in an article published by SOFT ROBOTS (SoRo) in 2019 [8]. To perform the experiment a blood vessel phantom provided by Elastrat was employed by the researchers. The method of purchasing phantoms from commercial providers reduces the amount of work required to produce phantoms on the researchers side and creates a possibility for them to focus on robotic systems or sensory equipment to be fitted on phantoms instead of the manufacturing of the non-smart phantom itself.

4 Robotic systems and sensory equipment used in recent phantoms

In recent times phantoms have often been fitted with robotic systems or sensory equipment in order to make their behaviour more realistic or to increase the amount of data produced when working with them. The complexity of such systems varies depending on the application. These range from increasing the realism of already existing phantoms to designing new phantoms built around a specific ability provided by electronic components.

A good example of a phantom being fitted with electronics to increase its realism is the previously mentioned study performed at the Toyo University [1]. In this work researchers tried to recreate a human blood vessel which would beat as if connected to a heart. This would function as a pre-stage to a full replication of a human cardiovascular system which could prove useful for many applications focused on interaction with the human vascular system such as catheter systems. Such systems might be influenced by the beating change of blood pressure inside human blood vessels and might thus benefit from a phantom simulating these pressure changes. In order to achieve this, a phantom was constructed using silicon tube to simulate the blood vessel itself as well as a diaphragm pump simulating a heart. Water was used as blood replacement. A function generator was used to control the diaphragm pump. In addition to this a 3-axis tactile sensor was placed directly below the silicon tube in order to measure the pressure generated inside the phantom. Both the data from the sensor as well as the input signal generated by the function generator were displayed using a oscilloscope simultaneously. Figure 6 depicts a schematic of the full setup.

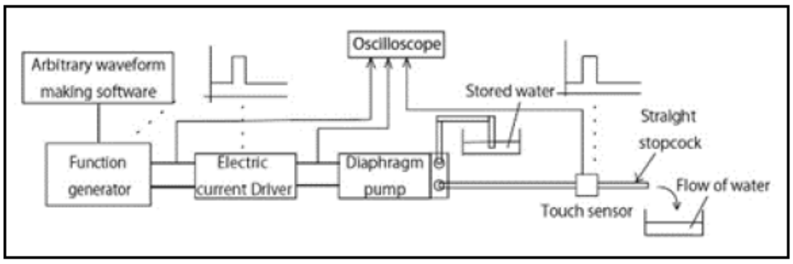

Figure 6: Experimental setup used at the study performed at Toyo University [1]

Using a diaphragm pump in order to simulate a heart has multiple advantages. The design of a diaphragm pump is by itself often similar to the heart as it employs a regular cycle of moving fluid through one or more chambers. Provided with a suitable control signal a diaphragm pump will produce fluid motion similar to a heart. This has also been used other studies proving its feasibility [9]. The pump used in the aforementioned work in depicted in figure 7.

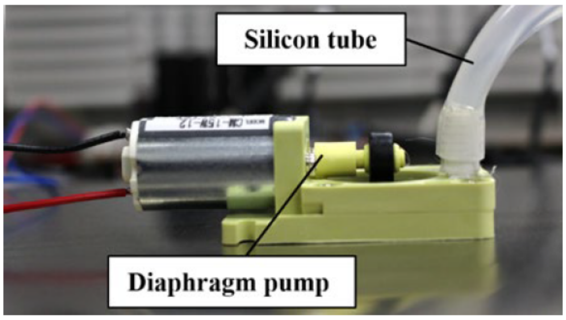

Figure 7: Diaphragm pump used to simulate a beating heart [1]

By plotting the data from the tactile sensor as well as the input signal for the diaphragm pump, scientists were able to determine the exact nature of the correlation between input current and phantom pressure to be a first-order lag system with a time constant of 1.3s. This information will be useful in the construction of realistic vascular phantoms in the future.

While incorporating this technology in existing phantoms will make them more realistic, other research projects have opened new ways phantoms may be used in the future by employing electronics. Such a research project was described in a paper published at the 3rd IEEE International Conference on Soft Robotics in 2020 [6]. In this study researchers describe their efforts to create a smart phantom simulating human skin, which was to be used to provide feedback to physicians training their ability to perform medical palpation. Medical palpation is a technique in which physicians use their hands to scan for abnormalities or tumors growing in or beneath human skin tissue. Such a phantom would be impossible without the use of sensory equipment.

In order to simulate human tissue the scientists used soft silicon (EcoFlex 00-10) which, as mentioned before, will provide resistance similar to human skin. To be able to offer feedback to novice practitioners the researchers had to incorporate a sensory matrix into their phantom which would be able to measure the amount and location of deformation inflicted to the phantom. This is a challenge as most sensors include silica and conductive metals which are significantly more rigid than the silicon which was to surround them. This would lead to an inhomogeneous structure unlike human tissue. Thus multiple Conductive Thermoplastic Elastomer (CTPE) sensors were employed. The sensors were placed in parallel lines with a constant distance between them, forming a rectangular grid. They were organized in two layers, one containing the horizontal, one the vertical sensors as shown in figure 8.

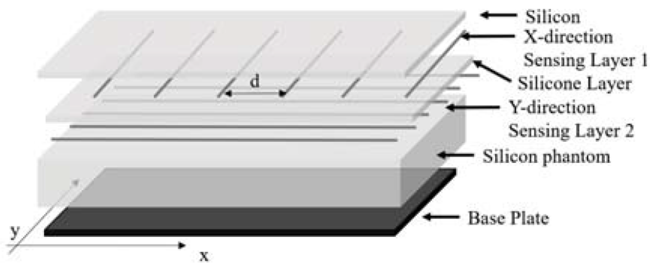

Figure 8: Structure of the phantom including sensory layers [6]

With this sensor setup as well as the usage of bivariate gaussian reconstruction the scientists were able to track deformation of their phantom with an accuracy of within ±5mm while also being able to measure the depth and width of the deformation as shown in figure 9. These measurements were achieved using a robotic arm and replicated using a separate human hand phantom.The fully assembled phantom can be seen in figure 10.

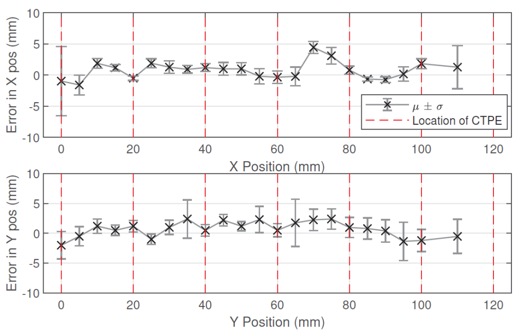

Figure 9: Errors observed in X-axis and Y-axis [6]

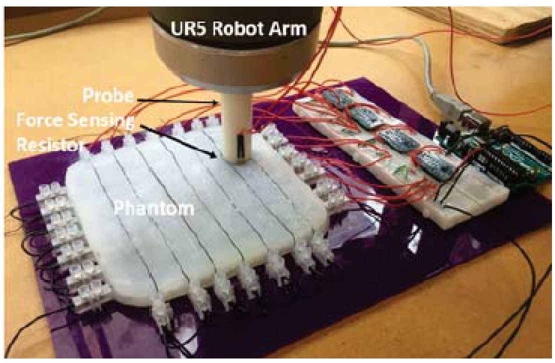

Figure 10: Robotic arm setup used to input the test data [6]

This technology provides a scalable, cheap method of measuring deformation on all kinds of human tissue phantoms. The type and alignment of sensors used by the researchers can also be used in different situations as they provide a tested way of measuring deformation of soft material. In addition it will be useful to training physicians, when applied to a larger humanoid surface.

Assisting novice physicians is an important application of smart phantoms. By providing them with real time feedback and analysis of their respective performances, smart phantoms can lead to accelerated training progress as well as better performance over all. Realizing this, some researchers have begun to retrofit commercially available training devices.

One such group of researchers, based at Obuda University in Hungary, has recently published a paper on their attempt at fitting a FRS (Fundamentals of Robotic Surgery) Dome with sensors in order to feed information to a custom program analyzing the performance of subjects [10]. The sensors used to obtain this information include load cells, capacitive proximity sensors as well as hall sensors and touch sensors. All of these were fitted inside or on top of the already existing training device. The sensors were connected to an Arduino Nano micro controller which was running a custom C++ program processing the data provided by the sensors. In Addition to this, image processing was used. The scientists also built a custom program, developed in LabView, running on a nearby PC which was to communicate with the micro controller in order to provide feedback on the performance achieved via a GUI. This data connection setup is depicted in figure 11.

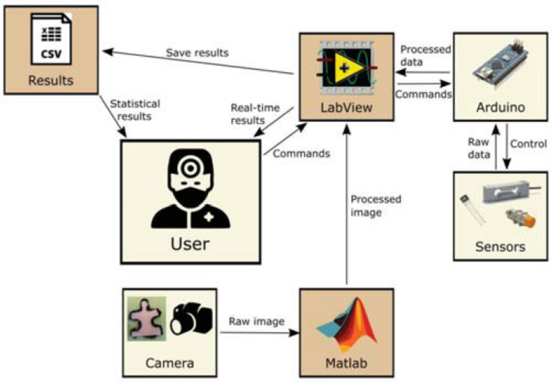

Figure 11: Diagram depicting data connections between the systems used. orange: on PC, Yellow: external [10]

This project is a good example of a phantom incorporating different kinds of sensors in order to achieve a wide coverage of aspects, needed to fully analyze a subjects performance. Arduino micro controllers provide a cheap and easy to use platform able to process and analyze data from such an array of sensors. As they include both input as well as output signal ports, Arduino micro controllers may also be used in order to control electronics built into smart phantoms. Because of this they are often used in prototyping and smart phantom construction. The incorporation of multiple pieces of software working together in order to process and display real time feedback is featured prominently as well. Implementing such data transfer structures makes the data, provided by increasingly complex smart phantoms, easier to work with for both developers and training subjects alike.

New sensors have been developed in recent years increasing the possibilities of data collection. One such sensor is the flexible pulsation sensor (FPS) [9]. This new kind of sensor makes it possible to measure pressure inside blood vessels. It can be employed both on living subjects as well as on vascular phantoms. This has been demonstrated by producing a vascular graft phantom on which the sensor was subsequently deployed.

5 Conclusion

Smart phantoms are vital for medical research in the future. With deployment of technologies such as 3D printing phantoms can be constructed simulating increasingly complex structures in a more realistic manner than achievable before. It has become possible to print Gypsium in complex shapes in order to simulate human bone as well as silicon, making realistic blood vessel phantoms possible. Traditional methods of manufacturing such as casting are used in junction with high tech methods, creating phantoms that profit from both. Companies have been created that specialize in the construction of vascular phantoms while others offer 3D-printing of many materials with different kinds of 3D-printers, making 3D-printing more accessible. Research has been conducted into how phantoms can be improved using both sensory systems and robotics alike. Pumps and actuators have been used to simulate moving parts or to create pressure changes inside phantoms. This makes research focusing on vascular systems more realistic as blood vessels can now be pressurized in a realistic way. Other phantoms can now move realistically giving research results more weight. Many kinds of sensors have been used to increase the amount of data produced by phantoms. These include sensors aimed to interact with external systems as well as sensors measuring internal conditions. The pressure inside blood vessels may now be measured much more accurately which makes vascular phantoms more realistic still. The deformation of soft phantoms is now measurable.

Combining these advances creates new possibilities in phantom construction and problem solving. Using modern techniques and materials in junction with sensory systems gives way to more accurate results.

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