Sensory Extension of a Tangible Object for Physical User Interactions in Augmented Reality

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Abstract: Tangible Augmented Reality (TAR) is a subclass of Augmented Reality (AR). It uses real-world objects enabling users to interact with the virtual environment. This can make virtual content easier to grasp and increase the users' immersion. However, the involvement of tangible objects in a TAR system is challenging. The system needs information on the interaction of users with the tangible object. Besides image-based tracking approaches that are commonly used for AR applications, additional sensors can be used to provide physical interaction possibilities for users. In this work, we investigate which opportunities hardware components can offer and how they can be integrated into a tangible object for a TAR application. We identify a taxonomy for categorizing sensors and control elements that can be used in a TAR setup and show how data provided by sensors can be utilized within such a TAR setup. At the example of a 3D print, we show how hardware elements can be attached to a tangible object and we discuss lessons learned based on a Unity TAR implementation. In particular, the discussion focuses on constructing 3D prints with sensors, exploiting hardware capabilities, and processing data from the additional hardware in a Unity application.

1 INTRODUCTION

Augmented Reality (AR) deals with the augmentation of the real world through virtual information. For instance, 3D organs can be superimposed on text pages enhancing 2D images in medical education. Tangible Augmented Reality (TAR) is a subclass of AR. It uses physical objects as input devices to make the virtual experience easier to grasp. However, providing interaction possibilities directly at a tangible object is not a facile task. Besides solutions that utilize tracking technologies based on image stream, additional sensors can be involved in a TAR setup to recognize user interactions. Furthermore, the sensors can increase tracking robustness for feature poor objects or varying light conditions. They can provide information on the tangible's orientation and environment which cannot be derived from a camera recording. In addition, the tangible does not have to be in the camera's frustum, which allows for an increased interaction space. Still, this involvement of hardware components remains largely unexplored and a practical description of technical details is often neglected in existing solutions.

In this work, we explore the integration and the usage of additional hardware components within a tablet-based TAR setup and make the following contributions:

- We propose a taxonomy that differentiates sensors and control elements for extending a TAR setup into three areas: Human-Machine-Interface, Object Properties, and Machine-Machine-Interface. Furthermore, functional requirements for tangibles and hardware equipment are stated.
- At the example of a 3D print from a real-world use case, we give detailed insights into our implementation process, showing how sensors, control elements, and communication interfaces can be integrated and controlled. We investigate a communication protocol based on byte lengths for the data transfer from a microcontroller controlling the additional hardware elements to a front end AR application based on the game engine Unity.

After the discussion of related work in Section 2, we present the identified taxonomy in Section 3 and describe the prototypical implementation in Section 4. In Section 5, we discuss optimization capabilities of hard- and software and give practical advice on how to design and implement TAR applications. Finally, Section 6 concludes our findings and points out directions for future work.

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2 RELATED WORK

There are various approaches to integrate physical objects into Augmented Reality. In the context of TAR, the term Tangible User Interfaces (TUIs) is often used. According to Zatulovsky and El-Sana (2019), TUIs enable users to alter the digital system's state by manipulating real-world objects that are represented with virtual counterparts. Billinghurst et al. (2008) define TAR applications to be built on the principles of TUI combining its intuitiveness with the enhanced display possibilities of AR.

A central characteristic of TUIs is the realization of physically embodied user interfaces, which allow direct and seamless interaction with the virtual environment (Günther et al., 2018; Huber et al., 2012; Ishii and Ullmer, 1997; Funk et al., 2014). According to Zatulovsky and El-Sana (2019), TUIs remove "one level of indirection in the interaction between a user and a system". In addition, they define physical objects as Tangible Input Devices to digital systems and emphasize their variety of forms and applications from everyday objects to abstract shapes.

Augmented Foam (Lee and Park, 2005), is a TAR setup based on 3D CAD data that helps designers to interact with the product during the design process. The authors address the correction of the occlusion of the virtual product by the user's hand. Whereas Augmented Foam can have various shapes, the ActiveCube (Watanabe et al., 2004) project focuses on the use of an abstract physical cube equipped with input and output devices to interact with 3D environments. In addition, the individual cubes can be connected to build more complex interfaces.

Zatulovsky and El-Sana (2019) present tangible stickers which can be attached to any everyday object. The stickers contain at least an accelerometer and a gyroscope. They also have a wireless connection to a server which then transmits the data to connected applications. In a user study with 38 participants, more than 70% said that the features of the physical object made the interaction better and that they felt more immersed.

Günther et al. (2018) create tangible chessmen by printing them with capacitive material. Therefore, standard touch surfaces can register these figures, making it possible to identify movements without additional active hardware components. Their focus was to enhance remote interaction between players over long distances and to offer the same experience as in co-located scenarios. In an informal study, the test persons stated that the combination feels almost like traditional chess. Furthermore, they felt strongly connected to their remote opponent, as they could observe his activity in realtime. In contrast to the previous approaches, however, they visualize the virtual contents via HMDs.

Kaltenbrunner and Bencina (2007) presented an open-source cross-platform computer vision framework, called reacTIVision, for the creation of table-based TUI. The physical objects were provided with fiducial symbols and visually tracked. The server searches the individual camera frames for the markers and then sends all identified symbols to a listening front end application. They can generate hundreds of unique fiducial markers that support a precise determination of position and angle on a 2D plane. Furthermore, each component of the system was implemented in a separately executable process. The communication was implemented using TUIO (Kaltenbrunner et al., 2005), a protocol that was designed especially for tabletop TUIs. Based on the analysis of a decade of development, various usage contexts, and extensions, the authors present the second generation of the protocol, TUIO 2.0 (Kaltenbrunner and Echtler, 2018), and an extended abstraction model for tangible interactive surfaces. With this, the authors integrate sensors abstractly into the context of a TUI. Sensors belong to the physical domain and are semantically encoded for later use in the high-level application layer. Encoded sensor data is transmitted to the interaction layer of the front end using the components defined in the TUIO protocol. There, it is decoded into objects, gestures, and events. The proposed model is hardware-independent and application invariant.

The overall structure of TUIs and TAR setups mentioned above mainly consists of two components: an object that is equipped with sensors and a wireless connection to a mobile display device. Recent work from Döring et al. (2020) presents four TAR-based interaction techniques ranging from common interaction on touch devices to the incorporation of an additional tangible object. They visualize structure and functionality of human skin using a tablet as magic lens (Bier et al., 1993). In addition to purely virtual extension, the authors also suggest equipping the real-world object with hardware components. In their user study, however, the focus is on interaction via the tablet and the use of a table as an interactive interface.

Generally, the progress in sensor technologies can be observed in many areas of our daily life, e.g., in the increased performance and equipment of smartphones or cars. However, these advantages are rarely published in detail. During our research, we found many examples of TUIs respectively TAR setups with integrated sensors, but no taxonomy for the description of the sensors. Only in the context of the TUIO 2.0 protocol, sensors were described abstractly. However, our literature research does not claim to be complete. Furthermore, only few works describe the concrete equipment of a tangible with individual hardware components. Practitioners could benefit from also stating technical details of TAR setups.

3 EXTENSION OF TANGIBLE OBJECTS WITH SENSORS AND CONTROL ELEMENTS

This section first deals with the categorization of a set of sensors that we identified to be suitable for providing interaction possibilities in TAR experiences. This helped to plan our TAR setup assigning a role to each sensor. The categories are superordinate areas, which can be filled project-specifically.

Furthermore, we aimed to create a transportable TAR application, which does not need special hardware other than the tangible and a display device. To allow free movement of the tangible, we chose a wireless setup. All hardware components are hidden inside the tangible itself so that the original surface features are not altered or obstructed. Thus, the TAR setup can still be supplemented by other methods such as image-based tracking techniques. Additionally, we assume the use of a mobile device combining portability with affordability. After the description of the categories, we outline the functional requirements for the TAR setup, especially for the creation of the tangible object.

3.1 Categories of Sensors and Control Elements

Conceptually, we identified three ways in which a tangible object can be equipped with additional sensors and control elements (see Figure 1). The first section on the left corresponds to the area of a Human-Machine-Interface (HMI). It describes two directions of communication: (1) How does a user directly interact with the tangible (HMI input), e.g., via buttons or other control elements? (2) How can the tangible respond to the user (HMI output), for instance by switching on an LED?

The second section is concerned with the tangible object itself and its environment. In the following, we will refer to sensors that analyze the object's properties, such as a location or an orientation, as positional sensors. For example, these can be accelerometers, gyroscopes, or magnetometers. Other sensors gathering data from the tangible's environment, such as humidity, temperature, or brightness, are described as environmental sensors. Figure 1 shows additional examples for each category. However, we do not claim to present a complete overview of sensors. Still, the classification of a sensor depends on the particular use case. For instance, temperature differences can also be triggered by human interaction. If that is intended as HMI input, not as object property, the sensor would be assigned to the first category.

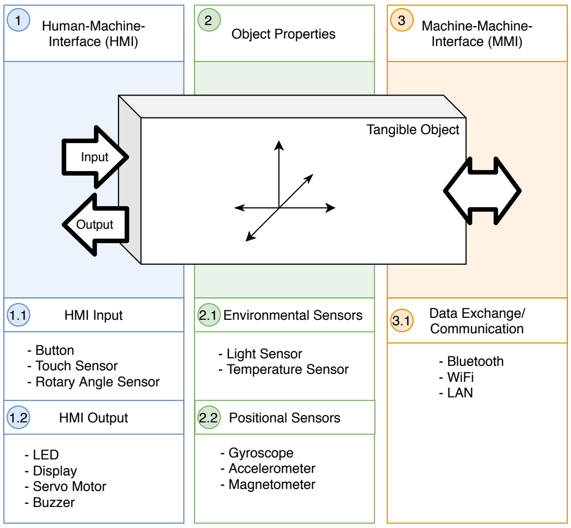


Figure 1: Categorization of sensors and control elements for an immersive AR experience with an exemplary assignment of sensors.

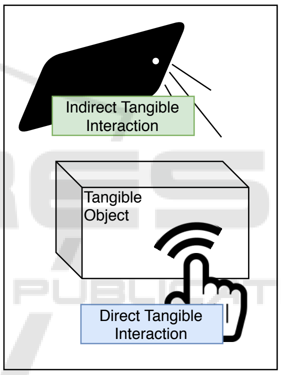


Figure 2: Direct and indirect tangible interaction.

Additionally, we distinguish the concepts of direct and indirect interaction with the tangible object. *Direct tangible interaction* occurs, e.g., when a button was pressed directly on the tangible's surface. *Indirect tangible interaction* applies when another source is needed to trigger an event, e.g., when the tangible is rotated to switch between multiple application modes, or a flashlight is used to influence the brightness values (see Figure 2).

Finally, the third section (Figure 1 right) describes the data exchange and communication with other machines (Machine-Machine-Interface, MMI). In addition to data exchange via wireless LAN and Bluetooth, sensors from the other two areas can also be used. For example, the illumination of an LED of one tangible object could cause a change in brightness of the sensor of another one and thus trigger an action.

3.2 Functional Requirements

Once the appropriate sensors have been determined, they need to be integrated into or attached to the tangible object. We considered three aspects in this process: The tangible's structure, the power supply of the electronics, and the communication with other devices.

If the tangible object already exists, the selection and the amount of possible sensors depends on the dimensions of the object. Since the electronics should be hidden inside the tangible object to not alter the outer appearance of the tangible, the interior must be hollow and offer enough space for sensors, cables, and control units such as a microcontroller. Besides the measurements of the tangible object, the choice of sensors depends on the object's material and vice versa. The material again influences the stability and durability of the tangible.

Apart from hardware-sided requirements, the tangible's dimensions also affect the usability of the application. Since the tangible needs to be moved freely, it must not be too bulky or heavy. Depending on how the virtual content is displayed, e.g., via HMD, mobile device, or fixed screen, it must be considered whether the user has to be able to move the tangible object with one hand or whether both hands are available.

Since tangible object and sensors form a self-contained unit, the power supply should be autonomous. For example, microcontrollers can be supplied by a small powerbank. However, it is important to consider not only the external routing of the necessary connections but also possible heat generation. Besides, the power supply can have direct effects on the functioning of other sensors such as magnetometers.

4 IMPLEMENTATION

To illustrate our concepts, we developed a prototype which uses a light sensor, a temperature sensor, accelerometer data, and a touch sensor to enhance a 3D printed skin model. In this use case, the skin model transports information about the structure and functionality of human skin. The user can view details of individual subcomponents and typical processes are simulated. This way, medical knowledge from textbooks is made available interactively. We designed the TAR application by selecting at least one sensor from each category described in Section 3 and evaluated how it can be used to display information about the skin model.

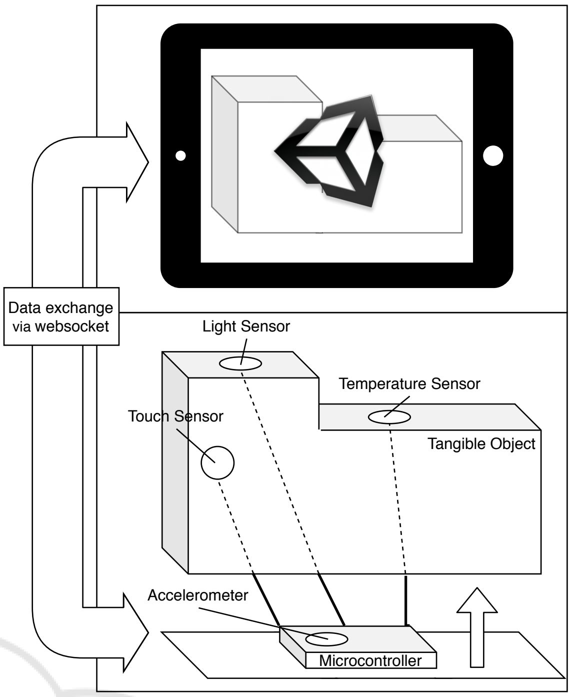


Figure 3: Main application components and sensor placement.

Figure 3 shows the main components of the application. The tangible object has sensors attached to it and hides a microcontroller inside. The front end application was developed in Unity, which supports multiple platforms and thus provides the possibility to view the virtual content on different devices. The application setup has a modular structure, which makes it easy to exchange sensors and representation frameworks.

In the following, we will describe how we planned to equip the skin model, considering which information could be visualized later on. Based on this, we set up the hardware including the 3D model of the tangible object. Then we show how we connected the sensors, transferred the data to the Unity application, and conducted the processing.

4.1 Sensor Choice, Placement and Hardware Setup

We chose suitable sensors for our use case based on the classification proposed in Section 3 considering the tangible object to be used in medical education. We started with the object properties and then proceeded to the external communication with users (HMI) and machines (MMI). Environmental sensors, to start with, can be used to simulate external influences on the skin. For instance, the data of the temperature sensor and a light sensor can help to visualize sweat production, the aging process of the skin, or the development of sunburn. Both sensors offer direct as well as indirect interaction possibilities, e.g. the light values can be decreased by covering the sensor with the hand or increased using a flashlight. This is directly available when using a mobile device with a flashlight to display the virtual content. Since both environment sensors visualize effects triggered by the skin surface, we placed the sensors on top of the skin model (see Figure 3). To render the virtual representation correctly, the current position and orientation of the tangible object must be determined. In this project, we focus on equipping the tangibles with sensors. Therefore, we use an accelerometer as a positional sensor instead of visual tracking.

The virtual content, i.e. the HMI output, is to be shown on a display. Since we mainly focused on how to use the sensor data to enhance a tangible object, any screen can be used to display the information. We decided to use a tablet, as mobile devices offer the advantage of already having integrated tools like the flashlight mentioned above. Other elements for displaying feedback such as LEDs or buzzers were not used here as they have no natural equivalents in the context of the skin model. For the HMI input, we used a touch sensor enabling direct interaction with the individual object parts. Finally, the sensor data transferred to the front end application, i.e. to a second machine by using a websocket interface the front end client can connect to. For the prototypical implementation, we used the LAN module of the microcontroller.

The microcontroller is mounted together with the powerbank on the base plate and aligned horizontally to convert the accelerometer data correctly (see Figure 4). For development, we chose to use a FRDM-K64F (NXP Semiconductors, 2016) microcontroller, which is pin compatible with Grove sensors (Seeed Technology Co., Ltd., 2020). Light and temperature sensors have been connected via two independent analog-to-digital converter (ADC) ports. The HMI input components, like buttons or touch sensors, can be connected via the digital ports. The on-board accelerometer can be accessed through the Inter-Integrated Circuit (I^2C) (NXP Semiconductors, 2014).

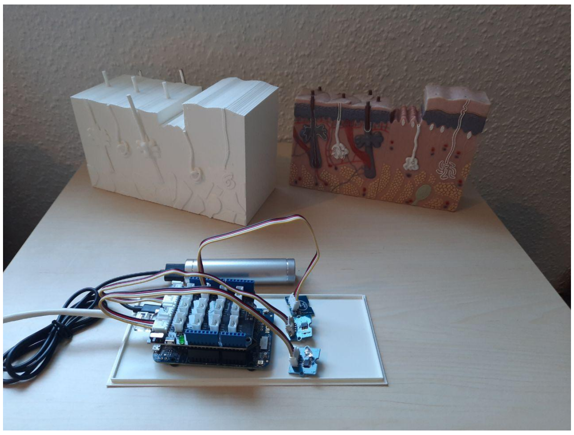


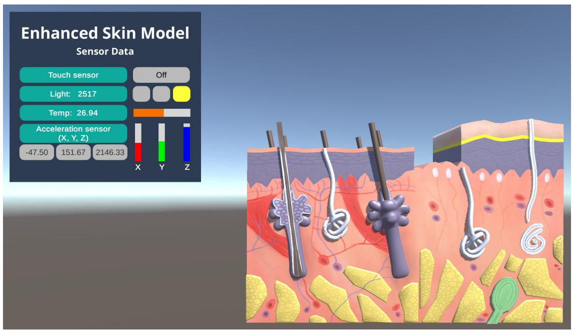
Figure 4: Previous model (right) and the newly printed skin model (left), K64F with equipped sensors and connected powerbank placed on the printed lid of the tangible object (front).

The 3D model's dimensions are based on a colored skin model and the development board sizes as we did not build our own hardware in the scope of this project. Figure 4 shows the hardware equipment with the printed tangible object on the left and the colored skin model on the right. Finally, the sensors are mounted on the inside of the model. For the power connection as well as for the LAN cable, appropriate openings must be provided to bring the connections to the outside.

4.2 Microcontroller and Data Retrieval of the Sensors

For development on the microcontroller, we chose to use FreeRTOS, an open-source real-time operating system for embedded systems. Compared to bare metal solutions without an OS, it requires additional computing and memory capacity, but allows a more high-level view on the microcontroller and supports multithreading. A separate thread can be used to manage each sensor leading to better code readability and maintainability. The ability to easily switch between different contexts compensates for the OS overhead and helps to use resources efficiently. In the FreeRTOS context, the term task is used synonymously for the term thread.

The application structure consists of one task for each sensor and a web server task providing a websocket to forward the sensor data to the front end application. All sensor tasks send their data to a queue,



Touch sensor Off
Light: 2517
Temp: 26.94
Acceleration sensor (X, Y, Z) -47.50 151.67 2146.33

Figure 5: The front end application visualizing the transferred sensor data of the equipped skin model.

depending on their sample rate. The queue item contains the data source, length, and a pointer to the actual data. Each queue item attribute is sent as a separate package within a superordinate frame containing the information of the connected client. The data retrieval is regularly triggered by a periodic interrupt timer (PIT) for all sensors except for the touch sensor. Each task configures a PIT controller channel to a different interrupt interval depending on the respective sensor. The accelerometer, for example, has the shortest interval as motion data needs to be updated most frequently.

4.3 Communication Protocol and Virtual Representation

In order to display the information in the Unity application the client is connected via websocket receiving the sensor data in byte arrays. The modular back end structure is mirrored in the front end using a main controller task to receive the data from the websocket and individual controllers for each sensor. Currently, the Unity application shows one label for each sensor with the transmitted data and a skin model prefab, a virtual representation of the tangible object, aligned to the acceleration data (see Figure 5). In addition to labels with raw data of each sensor, the values are visualized.

As soon as the websocket connection is established, the back end sends the data packets to the front end. The websocket controller writes each incoming message into the queue of the main controller, which forwards it to the dedicated sensor controller. There the package is decoded and the appropriate content is displayed on the tablet screen.

A complete data sequence consists of three packages containing the data source, length, and the actual data. The lengths of the packages form a byte pattern which is stored by each sensor controller individually and helps to check whether the sequence is complete and assigned to the correct controller. In case the data length of a packet does not correspond to the expected package pattern, the current sequence is discarded. In our application, all sequences start with one byte for the source and four bytes for the data length. Only the data length varies for each sensor. The byte pattern defines a unique communication protocol, which additionally allows to easily integrate further sensors into the application.

After the main controller has delegated the tasks, the individual sensor tasks can process the data independently. The back end directly forwards the raw data of the sensors to the front end. This way, the server does not have to offer several conversion variations and exactly those conversions can be made that are necessary for the virtual representation of the content.

The light and temperature sensor each send four bytes with the current voltage value. The accelerometer data consists of three values, one for each axis of the coordinate system. The acceleration is measured by means of the local gravitational field. This provides information on the accelerometer's orientation which allows, e.g., mobile devices to automatically switch between portrait and landscape. To align the skin model prefab we calculated the rotation around the respective coordinate system axis from the transmitted values. In accordance with aircraft notations, we use the following terms: yaw for z-axis rotation, pitch for x-axis rotation, and roll for y-axis rotation (NXP Semiconductors, 2017). Accelerometers, however, only allow to determine roll and pitch. Therefore, the tangible can only be tilted back and forth as well as from left to right.

5 DISCUSSION AND LESSONS LEARNED

To get an intention for the feasibility and the effort compared to the benefit of integrating hardware components in a TAR setup, we examined the individual components of our approach and identified possible weaknesses and optimization possibilities. The design of the concrete skin model enhancement in Section 4.1 already showed that only four sensors enable the representation of various virtual use cases. In this section, we will discuss our findings and state lessons learned from the implementation of the current system.

At the beginning of this paper, we presented the categorization we used to select the sensors. This helped to define at least one sensor for each area of the TAR setup and thus to define an immersive TAR experience for use in medical education. The functional requirements for the TAR setup are based on the assumption to create a freely movable, transportable TAR setup.

In the current implementation, the tangible is still connected to the display device via LAN, but this can easily be replaced by a WLAN module. However, the 3D model's dimensions should be adjusted more specifically to the actual size of the sensors to enhance the user experience. During the development process, the size was appropriate to be able to easily make changes to the hardware. Still, the print thickness needs to be reduced further, as it currently affects the sensors' efficiency. For instance, placing the temperature sensor inside the model causes it to react slower since the model's material needs to warm up first. So the 3D model's structure needs to take into account the characteristics of the sensors and be durable enough to prevent protruding elements from breaking off. Besides, openings for connections or special requirements of individual sensors, such as environmental sensors, could already be provided in the digital model for 3D printing.

Another optimization possibility is to use more specialized hardware for both the sensors and the microcontroller. This reduces the tangible's dimensions and weight and has also an impact on the overall performance and power consumption of the application. The integration of further sensor information, like the alignment of the magnetic field, could increase the robustness of the tangible's position determination. When using only accelerometer data, the model can wrongly be rotated by moving the tangible up and down quickly.

Adding the sensors is determined by the hardware layout, in our case the development board. Due to its task-oriented structure, however, our application can be extended flexibly to integrate further sensors and to try different transmission priorities and sample rates. Furthermore, the protocol used for the communication between the microcontroller and Unity application is a convenient, simple solution to transfer the data and interpret it correctly in the front end.

Still, the software on both sides is capable of further optimization. On the back end side, the use of PIT and ADC can be further optimized and a more object-oriented approach can be tested to accelerate the readout process of the sensors. Furthermore, many of the functions currently implemented in the software could be further accelerated by the proper use of the hardware capabilities. For instance, the Direct Memory Access (DMA) controller can perform memory operations without waking the processor. These optimizations can also reduce power consumption. Overall, comparative performance measurements should be conducted to get an indication of the effectiveness of the optimizations.

On the front end side, the distribution of incoming data packets could be parallelized by the sensor controllers automatically taking the appropriate packets from the entry queue. However, this requires to synchronize the access to the queue and to consider the occurrence of incomplete sequences. Still, this optimistic method increases the application performance, in case the probability of incomplete packets is relatively low. When introducing more restrictive synchronization mechanisms, the additional administrative effort needs to be included in the performance measurement. The effort is further increased by the fact that Unity functions such as the assignment of object attributes are not thread-safe.

Additionally, the sending rate of the back end has an impact on the optimization capabilities of the front end. If its update rate exceeds the processing in the front end, outdated data needs to be discarded to avoid the calculation of negligible values. However, the reception time of the respective package would also have to be managed for this.

Further optimizations could be made in the processing of the raw data and its virtual representation. To compensate for measurement inaccuracies, for example, an interpolation of the values between the individual frames could be incorporated. Overall, we can state many lessons learned from our approach for the integration of hardware and the use of sensors in a TAR setup.

6 CONCLUSION AND FUTURE WORK

In this paper, we investigated the extension of tangible objects with the help of sensors to provide TAR-based interactions. We assigned sensors and control elements to three main categories and formulated functional requirements for the tangible object. We developed a prototype choosing sensors based on our categorization and equipped the prototype with a light sensor, a temperature sensor, an accelerometer, and a touch sensor to enhance a 3D printed skin model. The application was built modular to allow easy extension by additional sensors. By describing technical details of the implementation, we gave practical advice on how to design and implement TAR setups. We also pointed out the limitations of the current implementation and listed hardware and application side optimization possibilities. These show the flexibility of the modular application structure and the potential for further add-ons.

In the future, more complex scenarios, feedback mechanisms, and the usefulness of the same sensors for displaying different content will be investigated. The sensor equipment can also be combined with other tracking and interface methods such as optical tracking or verbal commands. In case of a sensor fusion with optical tracking, the inclusion of sensors may compensate for shortcomings like tangibles with only few features. At last, we will conduct a user study to investigate the impact of tangible's size and weight on usability.

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