ACTO

A Modular Actuated Tangible User Interface Object

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ABSTRACT
We introduce a customizable, reusable actuated tangible user interface object: ACTO. Its modular design allows quick adaptations for different scenarios and setups on tabletops, making otherwise integral parts like the actuation mechanism or the physical configuration interchangeable. Drawing on the resources of well-established maker communities makes prototyping especially quick and easy. This allows the exploration of new concepts without the need to redesign the whole system, which qualifies it as an ideal research and education platform for tangible user interfaces. We present a detailed description of the hardware and software architecture of our system. Several implemented example configurations and application scenarios demonstrate the capabilities of the platform.

Author Keywords
Tangible user interfaces; tabletop interaction; actuation; prototyping platform; widgets; haptics; physical control.

ACM Classification Keywords
H.5.2. Information interfaces and presentation: User Interfaces - Input devices and strategies / Haptic I/O.

INTRODUCTION
Despite convincing benefits of tangible user interfaces (TUIs) over other input modalities, like intuitive use, immediate feedback or minimal necessary visual attention (cf. [5, 10, 21]), they are hardly found outside research institutions. Especially the field of actuated tabletop TUIs, where tangible objects can be actively moved by the computer, still seems to be in its infancy [18]. Although a number of promising concepts and systems have been reported (as presented in the Related Work section), there are only few quantitative studies or applications beyond proof-of-concept.

This might be related to the fact that the construction of a custom-built actuated tabletop TUI is a prerequisite for research in this field. Previously proposed systems are limited to a specific range of applications and setup options, as explained in the following sections. In addition there is a high technical construction effort. Considerable expertise in fields like robotics and electronics is required. This poses a substantial impediment and a high threshold for scientists to be able to contribute to this exciting research area.

To address this situation we propose a modular design strategy for actuated tangible user interface objects (ACTOs) for tabletops as a research and prototyping platform (Figure 1). Because of the high grade of modularity, typically integral parts like actuation mechanism or physical configuration can be individually customized and interchanged, allowing reusability for different scenarios and setups. The ACTOs can be equipped with different I/O devices, ranging from simple buttons to complex sensors. The system is also very mobile and can be set up quickly anywhere. Multiple of our ACTOs can be employed on any flat surface. In order to lower the entry-threshold we build upon large open communities (Arduino and Android). These provide the convenience of countless tutorials, setup guides and code snippets, which is of considerable benefit for the TUI research community and
also allows employment of the system for education in this area.

We present our design considerations, based upon extensive study of available literature, and elaborate on the developed hard- and software. We also report on several implemented example configurations and application scenarios to demonstrate the capabilities of the system. Even novices can quickly and efficiently extend our ACTOs, which is indicated by initial results from a feedback questionnaire.

It is our hope that our proposed system encourages and supports the exploration of various new concepts, application areas and quantitative studies, minimizing the time spent on the redesign of the system for different experiments.

**MOTIVATION & CONTRIBUTION**

Our motivation for this work originated from the idea to employ a tabletop TUI in a health related scenario. Existing published solutions in the area of actuated TUIs either report an actuation mechanism that is built into the surface with very high technological effort (e.g. [26]), and/or the tangibles lack flexibility in possible configurations (e.g. [20]). In any case the TUIs range of possible application scenarios is limited and in our opinion disproportionate to the high construction effort.

At present there are only few quantitative studies on tabletop TUIs and the same is true for general know-how on User Interface Design for TUIs. For comprehensive research studies a setup is needed that is useable for all kinds of scenarios, without having to spend weeks on redesign for every new experiment. It should be possible to investigate different input modalities and devices as well as various actuation mechanisms and tracking methods, without having to be an electronics expert. This would be beneficial for researchers and allow students to experiment with TUI concepts as well.

Addressing these premises, we propose a design strategy for ACTOs as a prototyping platform for research and education, which offers flexibility in almost any aspect. Our major contributions are:

- **Versatility:** The system is easily customizable in almost any way and the ACTOs can be equipped with a free choice of I/O devices like buttons, sensors and displays.
- **Reusability:** Our TUI is reusable for a wide range of scenarios, minimizing possible redesign times.
- **Actuation:** The actuation mechanism for movement is integrated in the ACTO, allowing the use on any flat surface. The integration of other actuation mechanisms like moving sliders is also possible.
- **Modularity:** Changing the physical configuration of an ACTO is a matter of minutes. Typically integral parts like actuation mechanism or tracking method can be interchanged.
- **Low entry threshold:** The integration of new hard- or software is alleviated through provided templates and the benefits of large open communities.
- **Mobility:** The system is self-sufficient and has no heavy or bulky components. It can be set up very quickly anywhere.
- **Extensibility:** Costs scale with the number of ACTOs, not the size of the working area.

**RELATED WORK**

Multi-touch surfaces became more and more common over the last years and a variety of new input and output devices are being announced day after day. Nevertheless well-known shortcomings like a lack of haptic feedback persist, one of many advantages of tabletop TUIs above other forms of input.

In this context the ActiveDesk by Fitzmaurice et al. [5] and the metaDESK by Ullmer and Ishii [23] have to be named, since their work laid the foundations for the field of tabletop TUI research. Both employ a rear projected display and electromagnetic tracking, but while the former introduces tangibles only as handles for digital objects, the latter directs more attention to the tangibles. They primarily use acrylic objects to minimize occlusion and introduce separate widgets like a passive scaling tool and a small active display on a supportive arm.

For their music interface reacTable Jordà et al. [11] employ simple passive tangibles tracked with fiducial markers. They provide their tracking framework reacTIVision and the TUIO protocol for tabletop TUIs openly [12]. Implementations are far spread in the open source community and include all major platforms.

For a general overview of the field we refer to the works of Shaer and Hornecker [22] or Karat and Vanderdonckt [13].

**Actuation**

In order to take advantage of the benefits of a tabletop TUI not only for input but also for output, the interface has to be bidirectional. Some form of actuation mechanism is required, so that not only the user but also the computer can actively move the tangibles. Brave et al. [2] demonstrated the first distributed actuated tabletop TUI with the PSyBench. Using two synchronized motorized chessboards, the system can position one object at a time with an electromagnet but does not control the rotation. With their Actuated Workbench Pangaro et al. [16] introduced the concept of actuated tangibles used for two-way communication with a computer system. They build an array of electromagnets under the surface of a table to position small pucks fitted with permanent magnets and an LED for optical tracking. However TUIs with an actuation mechanism built into the table involve high technological effort and are not very flexible in the size of the interaction volume or the mobility of the setup.
Rosenfeld et al. [20] use infrared controlled two-wheeled robots as a bidirectional TUI called Planar Manipulator Display. They are relatively big and slow, and aside from infrared LEDs for optical tracking, they do not provide any way to extend the available functionality. Kojima et al. [14] employ similar robots in an Augmented Reality game, the Augmented Coliseum. For tracking they integrate an arrangement of photo transistors into the robots to detect a fiducial on the display. They also propose extending them with additional features like pincers, but such a robot would have to be custom built [13].

Other inventive approaches include the Universal Planar Manipulator by Reznik and Canny [19] who propose actuating objects on a surface with vibration patterns. This is mechanically simpler than an array of electromagnets, but is relatively slow and has its limits for more complex movements. In a very recent publication by Follmer et al. [7], the authors describe actuating objects with their shape display inFRoM. With a 30 x 30 array of motorized pins passive objects can be mechanically lifted and roll or slide to an intended location. The constructional effort for the system is immense.

Modularity & Widgets

Ishii [10] underlines the importance of tailored design of a tangible for a specific function to benefit from natural affordances, at the same time preserving a balance to a more general approach for the reason of reusability. There are several examples in related work how the functionality of a tangible can be customized.

Sensetabile by Patten et al. [17] makes use of the capacitive sensing of two graphics tablets and electromagnetic tracking to localize a limited number of pucks. They provide a basic socket to attach very simple physical dials and modifiers. Weiss et al. [27] add tactile feedback to multi-touch tables by providing a number of passive widgets. These SLAP Widgets are made from acrylic to avoid occlusion of information. They include different knobs, sliders and even a keyboard, but basically represent overlays for touch input. None of these systems provide any form of actuation and with the exception of Weiss et al. they do not emphasize easy development of custom widgets for experimenting.

Weiss et al. [26] extend their acrylic widgets in more recent work with permanent magnets for actuation on a tabletop, calling them Madgets. The actuation is comparable to the Actuated Workbench [16], but the array of electromagnets is located under a TFT panel and in between the magnets there are fiber optic cables allowing optical tracking on the surface. The authors also use inducted current in the widgets, which allows the operation of very simple electronic components like a bell or an LED. Nevertheless more complex I/O devices like sensors would not be possible. Furthermore the system relies strongly on the electromagnets, which makes the setup relatively inflexible.

In the context of modularity and widgets, there are also a number of related projects beside tabletop TUIs. The ActiveCube by Watanabe et al. [25] is equipped with programmable microcontrollers. Several cubes fitted with sophisticated I/O devices like sensors, buzzers or lights form a network, providing the constellation and rotation of the structure. However to add new I/O devices, a complete cube has to be built. The individual cubes are relatively big and combining several ones results in a massive structure. A notable former Kickstarter project is Palette [4], a customizable physical computer interface. It is made up of a collection of individually combinable modules, each with a single input like a button, dial or slider. Various selections of ready-made modules can be ordered, but the design of custom modules is not possible.

There are some toolkits available intended for experimenting with hardware components for physical user interfaces, like Phidgets [8] or iStuff [1]. They aim at providing access to low-level components and I/O devices with a minimum of necessary electronics know-how. Nonetheless they are limited to a specific set of widgets and there are no similar examples for actuated TUIs.

DESIGN GUIDELINES

Investigating the related work in the field, a number of basic common requirements for a prototyping platform for tabletop TUI research and education become apparent. In order to be able to benefit from the natural affordances of a tangible and at the same time guarantee reusability for other applications, it has to be easily customizable to its specific function in any scenario (cf. Ishii [10]). In most cases tangibles are used in conjunction with a graphical display. Considering that display technologies for tabletops are manifold and in constant development, the tangibles we envision should be independent of the employed display and usable on any flat surface.

Furthermore it should be small to minimize possible occlusions of displayed data, as well as lightweight and wireless to avoid impediment or fatigue of the user. To be able to work with different tracking technologies, the integration of trackable components ranging from passive fiducial markers to active infrared LEDs should be possible.

Only active tangibles can provide the extent of flexibility we expect. Built-in inexpensive microprocessors should allow the integration of a wide range of components. They permit basic processing for the operation of a lot of active components at minimum costs. More complex calculations can be performed on a single more powerful host device. Although a mobile and self-sufficient setup would be desirable, it has to be kept in mind that in a lot of cases prototyping on a PC is advantageous, for example allowing access to existing libraries, separate I/O devices, multimedia, advanced computations, etc. Providing network integration would be important for different kinds of remote collaboration scenarios.
For a flexible TUI, scalability and actuation are important factors. An actuation mechanism that is integrated into the table means extending the working volume or changing display technology would implicate an immense effort. Including the actuation mechanism into the tangibles allows costs to scale with the number of tangibles and almost unrelated to the size of the table. In fact it would be preferable, if the actuation mechanism would be interchangeable as well and no special surface would be required.

Finally as a prototyping platform it should be easy to learn and quick to modify, but not limited only to special hardware or available sensors for example for a specific toolkit.

HARDWARE ARCHITECTURE

In this chapter we present our approach to meet the previously established requirements for a tabletop TUI prototyping platform. The most important part of the system are the ACTOs, which were partly inspired by the easy-to-use concept of Arduino, an open-source electronics prototyping platform.

We successfully employed the Arduino platform in student-courses with electronics novices for years because it is versatile yet easy to learn. A well-established community providing tutorials, setup guides and code snippets lowers the entry threshold for novices considerably, but also experts and researchers benefit from the available resources. Most importantly the platform is not limited to a specific set of electronic components, which is why we adopted the concept for our system.

Our strategy for the hardware is based on a flexible and modular design (Figure 2a) to allow the construction of customized actuated widgets. An Arduino compatible “Base Module” with RF communication capabilities can be fitted with an optional “Motor Module” which incorporates the desired actuation mechanism for positioning and rotating the ACTOs. On top of the Base Module there is a socket for mounting a custom-made “Extension Module” which can be equipped with arbitrary I/O devices ranging from rotary knobs over vibration motors to graphical displays. The integration of an actuation mechanism in this module is also possible, for example for changing the physical state of a slider or dial. The design of the individual modules is described in detail in the following chapters.

All employed Base Modules communicate wirelessly to a “Server” Arduino which relays all data to an “ACTO Server App” on an Android smartphone (Figure 2b). This smartphone acts as the central processing unit running the control software for the system, handling coordination of the ACTOs, providing a GUI and the tracking. Since the setup requires no heavy or bulky components it can be set up very quickly anywhere. If desired, all necessary functionality can also be accessed via WLAN. This allows the development of an application not only directly for the Android device, but basically on any WLAN capable system.

Base Module

We designed our Base Module (see Figure 3) inspired by the Arduino Pro Mini reference design. In order to save space we discarded minor components like the reset button from the original design. We exchanged the microcontroller for the more powerful Atmel ATmega328P clocked at 16 MHz and powered via 5 V voltage regulator. Once the Arduino bootloader is installed, it can be programmed as comfortable as a conventional Arduino board over the Arduino IDE with an FTDI USB to serial board by Sparkfun.
In contrast to most Arduino boards we enabled the analog pins A6 and A7, whereas we used A7 in a simple voltage divider configuration to provide low power shut off capability. For low power wireless communication we integrated the Nordic nRF24L01+ RF transceiver together with the necessary 3.3 V voltage regulator and a micro antenna. The transceiver is directly connected to the microcontroller via Serial Peripheral Interface (SPI).

On top of the Base Module, we devised a socket providing access to all available I/O pins supporting the easy attachment of custom Extension Modules. On the bottom a 4-pin socket and a power plug allow the connection of a Motor- and Tracking Module.

We put the Base Module into a casing that we produced out of acryl glass and nylon screw nuts. It also houses a 7.4 V LiPo battery with a capacity of 200 mAh. Openings for power plug and balancer connector of the battery as well as a power switch and a 3-pin socket for programming are cut into the housing.

Altogether there are 19 I/O pins, of which 4 provide PWM capability and 8 can be used as analog input pins. In addition 3.3 V, 5 V and 7.4 V are available as voltage source as well as 3 ground pins and 2 reset pins.

The size of the Base Module alone is 35 x 35 x 6 mm and it weighs 10 g. Including housing and battery it is 50 x 50 x 20 mm and 50 g. The hardware cost for one module is around 60 EUR.

Motor- and Tracking Module

In accordance with our modular design strategy, we devised an actuation mechanism which is completely packaged in a separate Motor Module and can be connected to the Base Module if desired. As a first example we decided to implement a two-wheel differential drive [9], since a comparable approach was already successfully employed in actuated TUIs ([14, 20]) and can be used on any flat surface. The simple mechanical structure and kinematic model are further advantages of this approach.

We used two metal gear motors with 1:50 reduction, rubber wheels and other small components for the mechanical part of the module (see Figure 4). The typically included passive caster wheel is not required, because the bottom of the module is less than 1 mm above ground.

The electrical layout of the module consists out of a 6 V voltage regulator and all the necessary components to build up two separate H-bridges. An H-bridge permits each motor to be operated independently from the other in both directions. In that way steering in any direction and turning on the spot are possible. The Motor Module is currently controlled over a connector to 4 I/O pins of the Base Module and powered directly over a separate plug to the battery.

However based on our experience for a second generation of Motor Modules we would prefer commercially available H-bridge drivers operated over SPI, which would free up 4 more pins for custom usage and also facilitate more complex modules.

The lowermost module of the ACTO has to include possible components for a tracking system, if required. If actuation is desired, the Motor Module therefore has to incorporate these components. Otherwise it can also be replaced by an optional separate Tracking Module. In our case we fitted the circuit board of the Motor Module with a mounting for fiducial markers to be used with a camera based optical tracking system. Just as well it is possible to integrate LEDs, photo sensors or other means of tracking.

Extension Modules

The extension and customization of our ACTOs is a core functionality of our system and should be as easy as prototyping with Arduino. For the integration of custom Extension Modules we provide a 27-pin socket, allowing access to all available I/O and power pins. We designed a template of the socket layout for Fritzing - a simple open-source layout tool for printed circuit boards (PCB). This software is much like Arduino designed in an easy-to-use spirit and supports in particular the process to transfer a circuit from a breadboard directly to a functional PCB layout. This makes designing an Extension Board especially easy for students and novices.

An Extension Board for our ACTOs can incorporate any component that can also be operated via Arduino. This includes simple I/O devices like buttons, speakers or sensors, but also motors for other kinds of actuation than movement of the ACTOs. Though in order to avoid damage to hardware components an absolute maximum of 800 mA can be drawn from the 5 V pin respectively 150 mA from the 3.3 V pin.

For a variety of possible Extension Modules and application scenarios please refer to the Subjective Evaluation section.
SOFTWARE DESIGN
Several frameworks for TUIs are available, which are adequate and relatively easy to use, like reacTIVision [12]. However we require a system which is independent of the employed tracking technology and provides support for an extensive two-way communication protocol. Therefore we developed our own framework (see Figure 5).

Its key components are the ACTO Server App on the smartphone with an Activity Template for comfortable application development, the ACTO OS on the tangibles which includes a template for easy integration of new Extension Modules, and a communication protocol to interface all components and a possible WLAN client.

The ACTOs provide only minimal computational capabilities to reduce cost and power consumption. More complex processing and all application logic runs on an Android smartphone. This allows versatile application scenarios, since the system can be set up almost everywhere in a short period of time. An application can be developed on the platform of choice and it runs on most current USB-host capable Android smartphones. A developer just has to write an app based on the Activity Template in the ACTO Server App to be able to access all public functions of the framework. A simple ACTO GUI allows direct operation of the most important functions and provides visual feedback.

Furthermore the framework handles incoming tracking data from a separate thread. The application allows an easy integration of different tracking methods, as long as translation and rotation can be provided in the form of floating point values for each tracked ACTO within a tracking volume. For our test setup we integrated the Metaio SDK 5.3 [15], a free to use Augmented Reality development toolkit providing various optical tracking methods. We employ the front camera of the smartphone for tracking. This has the advantage, that the touch screen is still accessible when the device is placed on or under an interactive table. The drawback on most smartphones is a lower resolution and frame rate, which is why the back camera can be used as well if no GUI is required.

A separate ACTO Service manages most of the functionality of the ACTO Server, answers to commands from the ACTO Activity, reports I/O events on the ACTOs and implements a simple communication protocol. The ACTO Playground includes multiple algorithms for operation of a larger number of ACTOs. It generates and controls movement paths to intended destinations, handles collision avoidance and implements calibration algorithms for the interactive surface.

Since it is often beneficial to use a PC or other platform to run application logic, all public functions of the ACTO Server App are also accessible over WLAN. On the client side only the implementation of a WLAN socket and our communication protocol is required. The downside of the additionally introduced (visually not noticeable) delay is counterbalanced by the benefits of being able to use already available libraries or input devices and developing on the system and IDE of choice.

An Arduino board is connected via USB to the smartphone and is fitted with an nRF24L01+ transceiver module for communicating with the ACTOs. This Arduino acts as a communication server and just forwards any complete communication messages to the appropriate receiver or rejects incomplete messages. To be able to use an Arduino board in conjunction with an Android smartphone we integrated an USB host serial driver library [24] in our ACTO Server App.
The ACTO OS on the tangibles is implemented in Arduino-Code, which is basically a C/C++ variant. A developer can specify the pins used for the components of a custom Extension Module and their nature (input or output, analog, digital or PWM) in the Extension Template. If set up correctly, ACTO Control will automatically update all I/O events with the ACTO Server App. The ACTO OS also implements a protocol for motor control, which represents all possible steering maneuvers and speed settings with 2 bytes. The actual code for operation of the Motor Module is implemented in a separate Motor Control class, in that way the same protocol can be used for different possible actuation modules. We implemented the code for our two-wheel differential drive modules and included for example a feature to minimize slipping tires and to allow calibration in case the motors produce slightly different thrust. For wireless communication using the nRF24L01+ transceiver we integrated the Mirf library.

**TEST SETUP & TECHNICAL EVALUATION**

As a test setup we used an 84 x 64 cm glass table with a height of 104 cm as presented in Figure 6. The smartphone running the ACTO Server App was a Samsung Galaxy Nexus GT-I9250. It features Android 4.2, a 1.2 GHz dual-core CPU, 4.65” display, a 5 MP back-camera and a 1.3 MP front-camera. The Server Arduino was an Arduino UNO r3 with a Sparkfun nRF24L01+ transceiver module. For tracking with fiducial markers we employed the front camera with a reduced resolution of 320 x 240 pixels for minimum latency.

The smartphone was placed together with the Arduino onto an adjustable beam under the table. This allowed us to experiment with different tracking volumes by changing the distance of the smartphone camera to the glass surface. Marker tracking is always sensitive to constant and uniform illumination. With ideal lighting situation we can extend the tracking space to the full size of the glass table. For a good balance between tracking robustness and interactive volume we adjusted the distance to achieve an approximate working area of 48 x 35 cm. In this setup the resulting update rate of tracking data was 30 fps.

These values are only exemplary since they are highly dependent on factors such as the employed tracking SDK and camera, distance to the table surface, lighting conditions and many more.

The threads for I/O handling and motor control are decoupled from the tracking process. The average round-trip time of an input event on an ACTO, processed by the Server App and transmitted to another ACTO for output was measured with 24.8 ms. We also determined the actuation speed of our two-wheel drive Motor Modules with 39 cm/s and a rotational speed of 120 rpm. The total power consumption without Extension or Motor-Module is about 56 mA, which would mean a theoretical operating time of about 3.5 hours.

Both motors at full power draw a current of up to 100 mA, generally making up the biggest part of the overall power consumption of our ACTOs and thereby reducing the operating time considerably depending on motor usage. With our 3.5 Ah charger, an ACTO is recharged in under 5 minutes.

**SUBJECTIVE EVALUATION**

In order to evaluate the suitability of the ACTO system as a prototyping platform for researchers and students, we tested how easy it is to learn to use and extend the system.

For that purpose we offered the participation in the project as optional courses for computer science students at a Federal Higher Technical Institute as well as for computer science master students at our university. In order to allow a valid conclusion on researchers and students, all participants were in their final years of study and had no special experience with electronics or robotics.

We observed them during the process of applying our system for the first time. The estimated time spent on different parts of the process was interpreted as a measure for the effort of each step. A total of 10 students of the technical institute (age 17 - 19) and 4 master students (age 24 - 28), altogether 4 female and 10 male students, participated in our experiment over the last 2 years.

Their assignment was to sketch an application scenario for tabletop TUIs and design and to construct the appropriate Extension Modules for our system. We helped with pointing them to recommendable tutorials, with conceptual questions and provided the required equipment, but other than that the students were free to experiment with the topic on their own. On average they worked 30.9 hours with our system. At the end of each project we used a questionnaire to get subjective feedback on their experience. It included an introductory part with a consent form and standard questions about age, gender and prior experience.
Furthermore we asked about the estimated time spent for different parts of the construction process, a subjective estimation of the complexity of the Extension Module and the overall satisfaction with the result. The estimated times had to be answered in concrete numbers, for the other questions the participants could choose from a 5-point Likert scale with the highest rating at 5.

The questionnaire also included a Critical Incident Technique (CIT) [6] allowing the participants to elaborate on their three most positive and three most negative critical events to reveal any specific problems. Furthermore we asked the participants to score the 10 items of the System Usability Scale (SUS) [3] to rate usability of “developing an Extension Module for the system”. The SUS generally provides a high-level subjective view of usability and is thus often used to compare usability between systems.

Use Case 1: Memory Extended
A group of three students of the technical institute called their project Memory Extended (Memex). They developed an audio memory game which works completely self-sufficient with two ACTOs. Their Extension Modules provide a differently colored 7-segment LED display including driver, a simple piezo-electric speaker and three differently colored LEDs (see Figure 7a). Later in the project they modified their original idea to a memory game for blind people which should allow them to learn conventional letters by following the movements of an ACTO with a finger. For that purpose the students replaced the display and the LEDs and constructed another Extension Module with a touch sensor and the piezo speaker for acoustic feedback. The students finished all Extension Modules and a simulation of the application, but did not perform user tests with actual blind people.

Use Case 2: Tangible Desktop Interaction
A completely different scenario was created by another five students of the technical institute. Under the caption Tangible Desktop Interaction (TDI) they devised an elaborate system for desktop interaction using two ACTOs in a Linux Ubuntu environment on a PC. Each Extension Module that they designed incorporates a vibration motor and two colored LEDs for direct visual and haptic feedback (see Figure 7b). In their scenario the ACTOs can represent icons or icon groups, windows or interface elements within an application. The current state is indicated by the LEDs on the tangibles and visual feedback on a traditional monitor. The ACTOs position themselves on the table according to their current function e.g. they move in and out of a designated taskbar region or take a position on the table relative to the currently represented item on the screen. The students implemented a number of tilt, rotate and move gestures to manipulate the icons and control a music player.

They also conducted a small scale user study to evaluate their application, but due to lack of experience in interpreting and handling tracking data it did not perform as well as they had hoped and the results were inconclusive. However the construction of the ACTO Extension Modules as well as the incorporation of our system via WLAN on a PC proved to be unproblematic.

Other Extension Modules
In addition to the already presented modules the remaining five students also developed a number of Extension Modules. Two students of the technical institute constructed two Extension Modules, each comprising an RGB-LED built into a rotary knob with an integrated button for a music composition application (Figure 7c). Two master students devised two Extension Modules that form breadboard like boards for prototyping directly on the ACTO (Figure 7d). Another master student integrated different sensors for measuring physical properties ranging from light-intensity to air-pressure into Extension Modules for a medical examination scenario. Finally a master student developed an alternative Motor Module (Figure 7e) based on a “bristlebot” approach [28] to reduce power consumption, mechanical complexity and make sliding the ACTO sideways easier.

Beside the presented examples, two students of the technical institute conceptualized an idea for optimizing the route of ships: Water and wind currents are visualized on a projected map on a table, where an ACTO in form of a ship can move along a route. A sail or rudder can be adjusted as input and in addition actuated with a motor for output. The effects of different sail/rudder angles on speed, route, etc. are updated in real-time. Unfortunately these students did not finish their project.
**Evaluation Feedback**

Six students (3 female, 3 male, 1 representative per group) answered the voluntary final questionnaire, which provides us with subjective feedback.

The participants reported above average computer science experience (avg. 3.6) and low electronics know-how (avg. 2). They estimated an average of 10.5 hours for studying basic principles and tutorials. The electronic assembly of their Extension Modules took 17.6 hours in average. Finally another avg. 1.8 hours were invested into the construction of a casing and only 1 hour (avg.) to write the necessary Arduino code for operating the module. All participants rated the overall satisfaction with the resulting Extension Module very high (avg. 4.3).

From the employed CIT a lot of positive and only few negative incidents were reported concerning our system. The range of possibilities for modifying the features of an ACTO was pointed out positively. The already extensive basic functionality was valued highly as well. The negative comments concerned basic problems related to a lack of experience with soldering, understanding the nature of tracking data and bugs in the Fritzing software. However one very helpful comment by one of the master students showed up a basic flaw in the system that we fixed later. Some of the pins we used for operating the Motor Module conflicted with the use of the Inter-Integrated Circuit (I2C) bus. We also scored the SUS, although considering the low number of participants we are aware that the results reflect a notion at best. A SUS score of 68 is generally considered above average. We got an overall score of 72.9.

**Possibilities & Limitations**

The diversity of the realized Extension Modules and use cases demonstrates, that the ACTO platform offers unprecedented flexibility. The possibility to integrate almost any electrical component allows the investigation of new application scenarios, for example a control scenario to coordinate the operation of emergency service personnel. ACTOs could be actuated on a map to present an overview of the current situation to an operational commander, who can at the same time issue commands by manipulating position and input components on the tangibles. The creation of “serious toys” as rehabilitation tools could also be investigated. A game scenario could be highly customized to a patient, while data from different integrated sensors would allow the analysis of the rehabilitation progress. Highly interactive educational applications could make abstract topics like optics more tangible. A predefined scenario could be presented with real lasers and lenses on ACTOs to demonstrate certain phenomena, while learners could manipulate the setting and see an immediate effect.

Because of the high modularity of the ACTO system, changing the physical configuration of an ACTO is a matter of minutes. It permits the exploration of individual aspects like different forms of actuation, tracking technologies or input and output modalities independently from each other. The system can be implemented as a whole but also in part and can be employed without a PC or additional display.

The presented Motor Modules can be used on any flat surface. Our current tracking solution requires a transparent table. This setup is very flexible and mobile which allows quantitative studies on the employment of tabletop TUIs. Since size and form of the ACTOs can easily be changed, user interface design studies for TUIs can be realized.

There are limitations of the ACTO system. The size of the Base Module of 35 x 35 x 6 mm without battery is an absolute minimum form factor. Depending on the power requirements of the Extension Modules, especially if more elaborate actuated output modalities are desired, a suitable battery can enlarge this minimum form factor considerably. Our current Motor Modules do not support actuation of the ACTOs sideways. In order to drive to a destination the ACTO first has to turn towards it and turn back after arrival. This increases the time to actually reach an intended location. The working area and update rate are limited by our current tracking solution. Since we employ marker tracking, a large distance to the surface or a bad lighting situation can cause wrong or missing ACTO positions.

**CONCLUSION & FUTURE WORK**

We present a novel, general actuated tabletop TUI system which is customizable in almost any way and thus reusable for a wide range of application scenarios. Our initial evaluation indicates, that the system is suitable as a prototyping platform for TUI research. It can be successfully used and extended after a relatively short learning time and without special knowledge of electronics or robotics. It advances research of tabletop TUIs by minimizing the time spent on the redesign of the tangibles for different experiments, thereby stimulating the exploration of new application areas and facilitating quantitative studies. The participants reported high satisfaction with the resulting Extension Modules and generally enjoyed the course a lot. Therefore we conclude that the system is also well-suited for educational purposes to teach TUI concepts.

Due to the positive feedback we will keep offering the creation of Extension Modules in an optional course for master students. We will also employ the system for research to study new practical application areas e.g. for haptic feedback in Augmented Reality and as a medical examination tool for children. Although the platform proved to be adequate, we continuously improve the system. We want to explore solutions for different limitations of the system. For example our current Motor Modules are not well suited for tilted surfaces. Therefore we examine the technology used for toy cars that drive on walls and ceiling through suction. Finally we also want to integrate a more sophisticated tracking solution based on laser sensing and are continuously improving the ACTO Server App to make development of new applications as easy as possible.
In order to allow fellow researchers to benefit the most from our results, we provide all the templates, material lists and software on our project webpage https://www.ims.tuwien.ac.at/projects/acto.

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REFERENCES