SPART – AN AFFORDABLE MOBILE AUGMENTED REALITY ALTERNATIVE TO INTERACTIVE TABLETOPS IN EDUCATION

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ABSTRACT

Technology to support collaborative learning has come a long way. Interactive tabletops support collaboration when correctly integrated in activity design. While these devices can now, in principle, be purchased by the general public, wide adoption in schools is hindered by their high cost and lack of mobility. In this paper, we analyze the potential technologies that could replace such devices. After developing a dozen prototypes to further test the potential of the most promising technologies, we found one robust, affordable and accurate solution: SPART (on-Surface Positioning for Augmented RealiTy) allows augmenting any flat surface (images etc.) with tablets or smartphones, addressing both affordability and mobility. This paper focuses on the technological innovations that were designed for SPART.

KEYWORDS

Mobile Computer Supported Collaborative Learning, Augmented Reality, Peephole Interaction

1. INTRODUCTION

Computer-supported collaboration has been found to positively impact learning (Dillenbourg, 2000). The design of appropriate software and hardware has long been a challenge in itself. In the 2000s, several custom interactive tabletop devices, that display dynamic information and allow user input, were designed and experimented for research purposes (Mateescu et al., 2019). In the following years, large touchscreen technology, as used for interactive tabletops, has rendered obsolete these custom setups and this technology has now widely proven its potential for collaborative learning. However, this technology is rarely used in educational contexts because of its high costs and lack of mobility, even though it could support new collaborative teaching paradigms (Aslan and Reigeluth, 2013).

Indeed, large interactive tabletops remain a non-negligible investment (2 000 € and above) for educational institutions such as schools. In addition, situated learning and alternative setups to classic configurations of one teacher – many students have evolved, alongside remote learning (Maqsood et al., 2021). Situated learning, during field trips in particular, calls for mobile collaborative devices that can be used outside classroom settings. This is not the case of current tabletops that weigh more than 100 kg and rely on an external power supply. Researchers are therefore turning to Augmented Reality (AR), which can be used through smartphones or tablets to display digital information on surfaces (such as traditional tables). However, classic, camera-based AR technology is not without issues for collaboration.

Firstly, if an image is augmented (*e.g.* a map of the world), the camera has to capture a critical portion of the image used as AR marker, which requires users to stand at sufficient distance and hold the device appropriately. This is not feasible over a long period of time with large smartphones or tablets, due to muscle fatigue (Pereira et al., 2013). Holding the device (especially with two hands for children) also makes interactions with virtual or physical objects difficult. Another issue is its interpersonal use within a group: If only one person is holding the device, other group members have to huddle around this person to see the augmentation. An alternate solution is for all members to use individual devices to work in the augmented space, but the focus on devices decreases awareness of what other group members or the teacher is doing, which is a major component of collaboration (Brudy et al., 2018).

These issues could be prevented if mobile devices were directly placed on the to-be-augmented surface (map, image, plan etc.). As shown in figure 1, this configuration, very similar to the one of an interactive tabletop, provides a common focal point for group attention and allows all group members to view augmentations while maintaining awareness on other group members' actions and keeping hands free. Furthermore, the mobile device serves as a convenient input method since its horizontal position on the surface allows for stability and is accessible from all angles.

Figure 1. SPART: on-Surface Positioning for Augmented RealiTy

While screen size is not directly proportional to collaboration quality (Zagermann et al., 2016), tablets still provide less screen space (typically 10") then tabletops (80" and above) to interact with. We therefore propose a peephole-type interaction that requires users to slide the device on the surface to see and interact with augmentations beyond the device's display. We call this setup SPART for on-Surface Positioning for Augmented RealiTy. It allows to augment static surfaces by sliding the device on it. It is suitable for use in schools being mobile and inexpensive (compatible with any available tablet or smartphone).

There is little research on such a setup which cannot be achieved with classic AR technology (the camera is obstructed as the device is lying on its back). A vertical augmentation prototype of a whiteboard has been developed by Sanneblad and Holmquist (2006) but has entailed issues with muscle fatigue and fear of breaking the tablet while holding it. To the best of our knowledge, no technology supports a horizontal peephole setup.

In this paper, we address the question whether it is possible to develop an affordable and mobile alternative to interactive tabletops and what type of technology is available and appropriate. Therefore, we initially identify the requirements of a potential device for teaching in classrooms and during field trips. We then review the possible technologies and evaluate them against these requirements. Technologies that fulfilled the most requirements resulted in prototypes. SPART-ME is currently the only prototype that fulfils all the requirements and is thus presented in detail in the second half of this paper. We then conclude with possible use cases for such a tool and future development perspectives for the presented prototype.

2. STATE OF THE ART

The peephole interaction described above requires the device's (smartphone or tablet) ability to accurately determine its position, relative to the surface it is placed on. In the following subsections we present the different technologies in modern mobile devices that exhibit the potential to do so. We also discuss their compatibility with the constraints related to supporting collaborative learning and using such technology in schools and outdoor settings (to support situated learning). Whenever a technology had the potential to satisfy these constraints, we developed prototypes to verify and test information on requirement satisfaction previously estimated during the review. All prototypes carry the name "SPART" with a suffix that identifies the used technology. More than 10 prototypes were created before SPART-ME, the variant presented in section 3.

2.1 Requirements

To guarantee an ergonomic user experience and a future use in the educational field and situated setting we identified the following requirements:

- **Accuracy**: The technology allows to retrieve the device's position with an accuracy of one centimeter or better. This assures that the user can easily associate the screen content with its underlying surface and that the virtual content is close to the real position of its static counterpart.
- **Fluidity**: When the device is slid on the surface, the technology allows for as little delay as possible when updating the image. The requirement to achieve a good reactivity is therefore estimated at minimum 10 position updates per second.
- **Minimum operating range**: A standard size for printed media in Europe is the A3 format, a surface of 29,7 x 42 cm. The technology should thus cover at least these dimensions.
- **Mobility:** Situated learning often uses learning contexts that mirror the educational content, such as field trips (*e.g.* for biology). The technology should therefore be portable: lighter than 500 g and not exceed dimensions of a notebook (A4).
- **Robustness:** The technology should function independently of outside conditions, such as sunlight, wind or ambient noise.
- **Affordability**: Potential use in educative setups depends on the possibility to deploy the technology in sufficient numbers. Thus, the device price should not exceed 50 € per unit.
- **DIY & Reparability:** Ideally, the technology should not require high skills in any specialized area and the production and assembly of a prototype should be within the range of educators or students. Components should be easily available; assembly should not require specialized tools or take long.
- **Multi-device support:** The technology should allow multiple devices to be located simultaneously to allow for multi-device scenarios (at least two).

For each evaluated technology, we verified if it could be excluded based on existent studies and using our requirements. When a requirement is met, it is marked with a "+", when there was evidence that criteria could not be met, it is highlighted with a "-" in Table 1. When unsure, a "?" marks the uncertainty aspect.

2.2 Localization Techniques

The localization techniques are presented in three categories, along with the possible technologies that can support them. The results are summarized in Table 1.

2.2.1 Dead Reckoning Techniques

Dead reckoning refers to localization techniques using object movement relative to its environment (speed, angle etc.). Those measurements allow to estimate device positions from an initial reference point.

Smartphones embark sensors in their Inertial Measurement Unit (IMU), some of which can be used to estimate the direction (gyroscope) and distance (accelerometer) from a known starting point. However, due to noise and required double integration in order to obtain a distance vector from an acceleration, this method is highly unreliable. We measured a 10 cm drift error after 10 cm distance from a reference point when used for positioning with small accelerations due to a high noise to signal ratio (*-accuracy, -robustness*).

Computer mice can be used to perform optical dead reckoning. However, the cumulating error builds up very quickly. In addition, uneven ground or imperfections in the surface increase the error (*-robustness)*. Another drawback of this approach is mouse drift since the rotation of the mouse cannot be distinguished from a translation and consequently is considered as the latter. Setups with two mice and external cameras can reach a maximum of 4 cm accuracy (*-accuracy*) (Sekimori and Miyazaki, 2007).

We also developed a hybrid prototype based on a **Magnetic Dead-reckoning technique**. A grid of small magnets attached to the surface allows the smartphone's magnetometer to sense a repeating pattern and count transitions between fields. If one or more movements are erroneous, the setup requires recalibration. In order for this technique to work, high sensor measurement frequency and precision are necessary. However, magnetometer modules in smartphones typically do not exceed read frequencies of more than 30 Hz (which is insufficient for moderate movements across thin field lines) (*-accuracy*). Hall-sensors can provide higher frequency readings but would require stronger (thus bigger) magnets, which decreases affordability and robustness as strong magnets attached to surfaces such as paper will easily stick together and damage it (*-affordability -robustness*).

2.2.2 Fingerprinting Techniques

Fingerprinting is a technique that relies on sensors within the device to measure unique values of its environment at every position, or inversely an environment capable of sensing the device (*e.g.* a touchscreen)

Switch grids can be used to implement this technique. In its most basic form, a keyboard is a fingerprinting device, localizing finger position with an accuracy of about 2-3 cm (and associating the position to a symbol or letter) by physically closing a circuit in a grid of switches. For such localization approaches to work, the device must reliably trigger switches sufficiently small to provide an accuracy above 1 cm. While theoretically possible, the number of switches (1260 to cover an A3 sheet) required for 1 cm accuracy requires extensive wiring (*-DIY*) and is costly (*-affordability*). **Capacitive grids** suffer a similar issue, since a high number of electrodes must be wired. Additionally, a device can't be distinguished from another (*-multi-device*).

NFC tags can be used to create an artificial environment for the NFC reader of a mobile phone to read location information off those tags. The SPART-NFC prototype was developed with an NFC grid. Each tag has absolute position information stored that can be read by a smartphone placed on a tag. This prototype was abandoned due to an accuracy of less than 2 cm (NFC antenna range and size) and a read frequency of less than 10 Hz leading to a high rate of missed NFC tags (*-accuracy*, *-fluidity*).

Magnetic fingerprinting can be used with magnetometers in tablets and smartphones which have the capacity of measuring magnetic fields in three dimensions. By creating artificial magnetic fields with Neodymium magnets, the smartphone can fingerprint the field and use a mapping (position per field value triple) of the field to determine its position. We developed SPART-MA-F, a high-accuracy prototype limited to a surface of 20x20 cm due to the rapidly declining magnet field strength (*-range*). Creating an equally heterogeneous field with multiple magnets to overcome size limitations was tested but did not prove reliable (*-robustness*) due to variation in field strength and symmetry in commercially available magnets.

Similarly, fingerprinting can also be used with wave-based technologies such as **Wifi, Bluetooth or acoustic waves**. These waves have a signal strength that decreases with distance. It is therefore possible to read the signal strength of waves from different emitters for known locations. However, due to reflection and overlapping, accuracy beyond four centimeters is not possible (*-accuracy, -robustness*) (Wang, Yang and Sun, 2018). Driver software and operating systems also limit frequency of signal strength readings *(-fluidity).*

Infrared ink codes are a recent technology developed in educational speaking pens. This technology relies on a small infrared camera, integrated into the top of the pen, which reads a code, printed with infrared ink on the page of a book, invisible to humans. While it would be possible to print codes with distinct location information codes on a surface and attach such a small and cheap CMOS camera with a microcontroller to a smartphone, position could only be retrieved in slow movements or when the device is at rest (*-fluidity*). In addition, the special ink is not widely available (*-DIY)* and the longevity of the ink under environmental influences such as sunlight is uncertain (*?robustness*).

Computer vision is another optic passive fingerprinting technology. Visual tracking technologies are used for Augmented Reality by detecting the position of an object within the field of a camera in order to add object-dependent information to its position on the screen. An implementation with a smartphone displaying a marker and another smartphone running tracking software would work best for high angles. However, the additional smartphone increases cost (*-affordability*) and would require an apparatus to hold it at a minimum height (*-mobility*). The technology is also prone to variable light conditions and occlusion from a hand moving the smartphone (*-robustness*).

An active **sonar** technology with an accuracy of 1 cm has been developed under the project name "FingerIO" (Nandakumar et al., 2016). Any device with two microphones and a speaker can localize fingers or other objects around a smartwatch or a similar device. Therefore, we deduct a possible implementation in a smartphone that locates itself in reference to a small object on which the emitted sound waves get reflected. This technology is, however, not available since it is currently commercialized and thus disclosed. It also seems unfeasible to distinguish different objects, making the use of multiple devices unlikely (*-multi-device*). Also, the noise of a sliding phone would likely interfere with measurements and position could only be retrieved at rest (*-fluidity, -robustness*).

Radar and LIDAR cannot achieve accuracy beyond 10 cm (in the case of commercially available LIDAR sensors) due to the speed of light with which their emitter waves propagate (*-accuracy*).

2.2.3 Triangulation and Trilateration Techniques

The use of geometry to respectively use either angle or distance to known points in space is a widely used localization technique.

GPS, Wi-Fi and Bluetooth wave-based localization techniques are particularly well studied and initially seemed promising. Indeed, modern smartphones include communication modules for various wavelengths: Bluetooth and Wi-Fi (2.4 & 5 GHz), GSM (900Mhz) and GPS (1600Mhz). However, these are not accurate enough for our use case (< 1cm). GPS can reach up to 30 cm at best (Moore, 2017) but depends on a variety of factors and cannot be used in buildings. Bluetooth or Wi-Fi accuracy does not exceed one meter while GSM triangulation is limited to 500 m (-*accuracy*). UWB is a recent development of a sensor capable of emitting bursts of electromagnetic waves of different wave lengths to detect objects at close proximity but the accuracy does not exceed 10 cm (-*accuracy*). Internal GPS, Wi-Fi and Bluetooth modules also do not provide sufficient reading speeds (scans containing wifi strength information) to obtain adequate fluidity (-*fluidity*).

Smartphones also contain **acoustic** receiver and transmitter modules (microphone and speaker). Sub-centimeter accuracy has been achieved for example by Qi (2017) in an indoor setting with specialized hardware (+*accuracy*). However, sound is reflected by obstacles and signals of emitters must be filtered from ambient noise, reducing accuracy when used with a conventional smartphone, therefore increasing computational complexity and requiring hardware with costs above 100 € (-*affordability*).

Light triangulation consists of a laser (point or line) and a camera located above or beneath the laser at a given angle. Where the laser hits an object, the camera can filter the point/line of the laser and the position can be retrieved by taking into account the angle of the camera and the position of the laser within the field of the camera. Xiao and Scavella have managed sub-centimeter accuracy in a DIY 3D scanner project (Scavella, 2020). They noted however difficulties with different types of object materials, reflecting or dispersing laser light (-*robustness*). The approach has its limitations in the angle of view of the camera (similarly to fiducial markers) and requires at least an embedded system such as a Raspberry Pi and a camera (-*cost*).

Mechanical trilateration techniques can also be used by attaching physical strings to the device and measuring their length. Sensors such as potentiometers are accurate (+*accuracy*), widely available (+*DIY* & reparability) and measurements can be read at high speeds (>10 kHz) (+*fluidity*). However, space is required to house reels for the strings and a rigid support is required, reducing mobility (-*Mobility*).

Table 1. A summary of the technology review and (*) prototypes

Technique	**Technology**	**Requirements**							
		Accuracy	Fluidity	Range	Mobility	Robustness	Affordability	DIY	Multi-device
Dead reckoning	Smartphone dead reck.*	-	+	+	+	-	+	+	+
	Computer mice	-	+	+	+	-	-	+	+
	Magnetic dead-reckoning*	-	+	+	+	-	-	+	+
Fingerprinting	Switch grids	+	+	+	+	+	-	-	+
	Capacitive grid	+	+	+	+	+	-	-	-
	NFC tag grid*	-	-	+	+	+	+	+	+
	Magnetic fingerprinting*	+	+	-	+	-	+	+	+
	Wifi/Bluetooth/Acoustic	-	-	+	+	-	+	+	+
	Infrared ink	+	-	+	+	?	+	-	+
	Computer vision	+	+	+	+	-	-	+	+
	Sonar (FingerIO)	+	-	+	+	-	+	+	-
	Radar and Lidar	-	+	+	+	+	+	+	+
Triangulation/ Trilateration	GPS/WIFI/Bluetooth	-	-	+	+	-	+	+	+
	Acoustic trilateration*	+	+	+	+	+	-	+	+
	Light triangulation	+	+	+	+	-	-	+	+
	Mechanical trilateration*	+	+	+	-	+	+	+	+

Review Conclusion. Our literature review, experimental developments and tests are summarized in Table 1. Accuracy is an issue for any dead reckoning technique. These technologies also share a lack of robustness. For passive fingerprinting techniques to work, some artificial layer for the device's sensors is necessary, which generally entails issues of robustness or complexity. The creation of a reliable overlay (in the case of magnetic fingerprinting and NFC) which doesn't get distorted by environmental conditions is a challenge. Active fingerprinting methods are less prone to environmental variability due to the use of an emitting signal but either lack accuracy or are costly. Finally, the triangulation and trilateration techniques seem the most promising, especially the ones based on acoustic and mechanical trilateration. Thus, we focused on the development of the SPART-AC and SPART-ME prototypes. SPART-AC could not provide its theoretical accuracy at the time of writing. Even though simulations predict sub-centimeter accuracy, the use of the prototype in real contexts shows accuracy issues due to ambient noise and objects (hands) that the acoustic waves bounce off of. The SPART-ME prototype, developed to test mechanical trilateration was the most successful in living up to the predictions from the technology review. We present this prototype in the next section.

3. SPART-ME

SPART-ME uses two string potentiometers to implement a MEchanical trilateration technique that relies on the length of the unwound strings between the object and two known points in the 2D plane (see Figure 2). The smartphone (1) is held within a custom plastic frame (2). To this frame is attached a metal ring (3) on which the ends of the potentiometer strings (4) can slide when the smartphone (1) is moved.

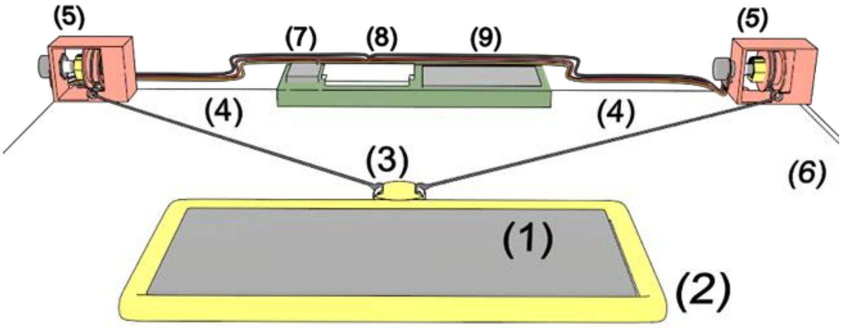

Figure 2. SPART-ME: Two 3D-printed string potentiometers (5) linked to an ADC (7) providing 15 Bit precision of the measured length connect to a microcontroller (8) sending data via a Bluetooth interface to the smartphone (1)

Mechanical parts of the string potentiometers and housing of electronics can be printed with conventional fused deposition modelling 3D printers. The two string potentiometers (5) are attached to a support (6) and their voltage divider pin is connected to a dedicated analog-to-digital converter (7). Both analog-to-digital converter and potentiometers are powered from the 3,3V pin of a microcontroller (8). The microcontroller (8) and analog-to-digital converter (7) are connected via a four line I2C connection. The microcontroller (8) is powered by a battery pack (9) or an external power supply.

3.1 Performance

Accuracy. To assess the accuracy of the prototype, we compared the real position and calculated position on 81 positions on a 9x9 grid (at positions every 5 cm, covering an area of 45x45cm) The mean error for the current prototype is 0,4 cm. The error increases with distance (but also very close) to the potentiometers and especially in the center of the x-axis. It fulfills the accuracy requirement of an average error below 1 cm.

Fluidity. Currently, the refresh rate is set to 15 positions per second. It can be increased by setting the communication speed between the device and the microcontroller. The current speed was chosen to reduce power consumption.

Minimum operating range. The current prototype can effectively cover a surface of an A2 sheet, limited by the strings' length, the reels' diameter and the potentiometers' limitation to 10 turns. Increasing the wheels' diameter and strings' length allows to increase the operational range but will reduce accuracy.

Mobility, Robustness, Affordability & Reparability. In terms of mobility, the weight of the battery-powered prototype is acceptable (700 g) but it is cumbersome to transport because the potentiometers have to be attached to a rigid support. The prototype is robust since it is immune to sunlight and noise. The entire prototype is affordable since it can be produced for 80 € as a mobile version or 50 € for a version that has to be connected to a power supply: Two 10 turn potentiometers can be purchased for 30 €, keychain holders are available for 2 €, an ADS1115 analog to digital converter for 5 €, a microcontroller with Bluetooth (e.g. Seeed XIAO NRF52840) for 10 € and the remaining parts can be printed with a standard 3D printer for under 2 € filament cost. Finally, the assembly of the prototype requires soldering skills and is accessible to most DIY hobbyists. A detailed guide still needs to be tested with the local technology school teachers.

3.2 User Software

Several applications have been developed for SPART-ME. A first application was designed to augment the map of a city. It allows the user to see icons for important buildings and to click on them to open an information window. In addition, we implemented six buttons to change the layers shown on the map (satellite humidity images of different years to show the impact of climate change on a local scale). The buttons are also sketched on the paper map (and are therefore visible at all times) demonstrating the use of static interfaces that become interactive when the device is slid on the interface.

Another application was developed for and tested with students in middle-school. It features virtual overlays with seismic data on an A3 world map and access to vertical depth position of earthquakes at predefined positions. Students had to identify tectonic plate limits and relative movement types (*e.g.* subduction) in this activity. The activity was structured in a coloring, classification and hypothesis building task. The prototype was promptly adopted by students who reported a positive user experience. Results point to low cognitive load in the use of the unfamiliar interaction type and the movement of the tablet seemed to support spatial reflections by students as well as collaborative coupling styles. Indeed, in a later interview, a student stated that even when not actively engaged with his peers, the tablet was a good visual indicator on what his peers were working on, thus allowing him to visually keep track of the group activity while reflecting on a related problem. In another instance, students engaged in lengthy off-topic conversations and picked up their peer's work without transition after having regularly checked the tablets position on the table from a distance. The prototype operated flawlessly throughout the accumulated nine hours of use.

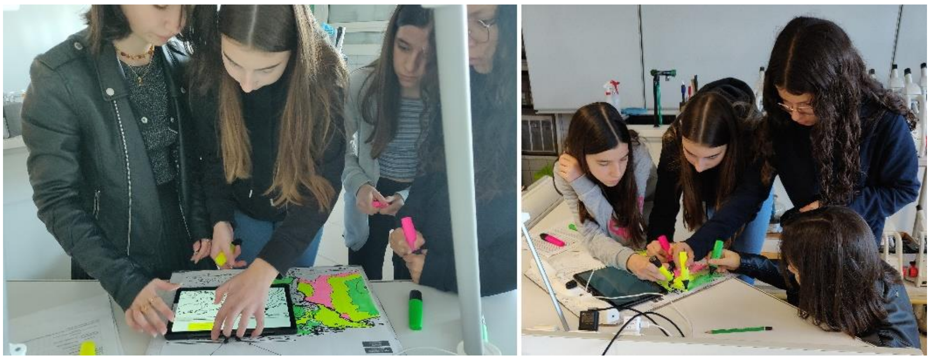

Figure 3. A group of students using SPART-ME to augment a tectonic map

In a recent development, the system has been modified to use weights for retraction of strings and 3D printed hall-sensor based rotary encoders. This effectively removes the space limit and reduces part costs to 20€ per unit. This variation can be used to create affordable smartboards (in conjunction with a projector) and augment large wall mounted maps. Strings and weights configured to counterbalance the weight of the attached device mitigate muscle fatigue or fear of breaking the device as in the experiment of Sanneblad and Holmquist (2006).

4. CONCLUSION

In this paper we reviewed localization technology and techniques under the angle of eight requirements typical for use in classrooms and during school trips. This review provided insights on promising, available technology to create accurate, fluid, robust, affordable, easy to maintain and multi-device compatible prototypes. Consequently, we presented SPART-ME, a prototype to investigate the interest of peephole interactions for mobile computer-supported collaborative learning to mimic a mobile interactive tabletop. The prototype fulfills all requirements with a variety of applications and a positive outlook for improved affordability and mobility. While the benefits for collaborative learning still have to be confirmed by large scale user studies, the technology has already been successfully used in an in-classroom study pointing towards benefits for collaborative learning. We can thus answer positively the question whether the hypothesized device can be developed and that the most accessible technology seems to be a mechanical trilateration. Finally, SPART is not restricted to educational applications: affordable interactive museum panels, augmented annotation tools (for plans), decision-making tools for team meetings are possible

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