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Put That Needle There: Customized Flexible On-Body Thin-Film Displays for Medical Navigation

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Informed by modern imaging techniques, current medical navigation systems support physicians during a variety of interventions, such as needle-based operations. During these, an abundance of information is often displayed on monitors placed in positions that are uncomfortable for the operator to view. In this article, we address these issues with the concept and prototype of a customized flexible display that is placed on the patient's body to provide the essential information at just the right location. We present an empirical evaluation comparing the flexible display against a control condition using a standard interventional monitor setup and an additional condition that combines both. Our results show that the flexible display significantly reduces task load while improving overall usability. Furthermore, we found indications that the flexible display reduces task completion time while also observing a negative effect on accuracy, which needs to be balanced carefully.

CCS Concepts: • **Applied computing → Health care information systems**; • **Human-centered computing → Displays and imagers**; **Empirical studies in HCI**;

Additional Key Words and Phrases: Intra-operative information, electroluminescence, task load, needle-based intervention

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1 INTRODUCTION

Surgical and medical navigation systems have pervaded the operating room (OR) [24]. They make difficult interventions safer and enable new forms of surgeries that initially had been too risky or impossible. However, one major challenge with using navigation systems in the OR is how to provide the data to the physician.

There are three main design challenges for providing visual navigation information. The first challenge is the possibility of information overload. Modern medical imaging technologies such as computed tomography (CT) or magnetic resonance imaging (MRI) provide a vast amount of data—too much to be digested by the surgeon during an intervention. The second challenge is finding suitable technology, and the third is determining the best location to display the information.

Although research has proposed a variety of solutions [4, 7, 13, 22], discussed in the following section, state-of-the-art systems almost exclusively rely on computer monitors placed on a stand or hung from the ceiling [24]. Due to space and hygiene restrictions inside the OR, optimal placement is often difficult to achieve. This leads to situations in which the surgeon does not have an easy and ergonomic view of the monitor. Especially if the monitor needs to be placed at a wide angle with respect to the operator's field of view and the situs,[1] viewing the monitor during an intervention is awkward and introduces additional cognitive and physical strain on the surgeon or radiologist.

We address these problems with our concept and prototype of customized, on-body displays (Figure 1). Customized, special-purpose displays allow reducing the information to what is essential for a specific task. By using a manufacturing approach that allows printing these displays on a variety of surfaces [25], including thin foils and paper, the displays can be attached directly onto the patient's body or onto the operator's clothing, placing them conveniently into the center of the operator's field of view.

We chose needle-based interventions, specifically radio-frequency ablation (RFA), as a first testbed for our displays, although our concept could be generalized for other navigated interventions as well. During RFA, a needle's tip must be placed at the intended location inside the patient's body to ensure complete ablation of the tumor. After the needle is placed correctly, high-frequency electromagnetic radiation is applied to induce heat that destroys the tumor cells.

Typically, navigation information is derived preoperatively from segmented and annotated CT or MRI images. Thereafter, a radiologist or surgeon specifies the target location along with the point of insertion and the desired insertion angle. During the intervention, the needle and the patient's body are tracked in real time. The current orientation and position of the needle in relation to the defined target position and orientation are presented on a monitor.

Our concept builds on the exact same preoperative data and real-time tracking. The important differences include the special type of on-body display and the customized visualization metaphor. We developed an intuitive circle visualization to guide the needle orientation and a nonlinear depth progress bar to guide the needle insertion depth (Figures 1, 2, and 3).

This work's main contributions are (1) the novel application of customized screen-printed electroluminescent (EL) displays to the medical domain, (2) the concept and prototypical implementation of a flexible on-body display to guide needle-based interventions, and (3) results of an empirical evaluation.

Our results show that the flexible display significantly reduces task load while improving overall usability. Additionally, we found indications that the flexible display can reduce task completion time while also observing a negative effect on accuracy that needs to be balanced carefully.

2 RELATED WORK

Computer-assisted surgery is a growing field of research that increasingly supports and advances the work in the OR. Within this field, especially the support of navigation in surgery [24] is a timely and important topic at

[1]Field of operation.

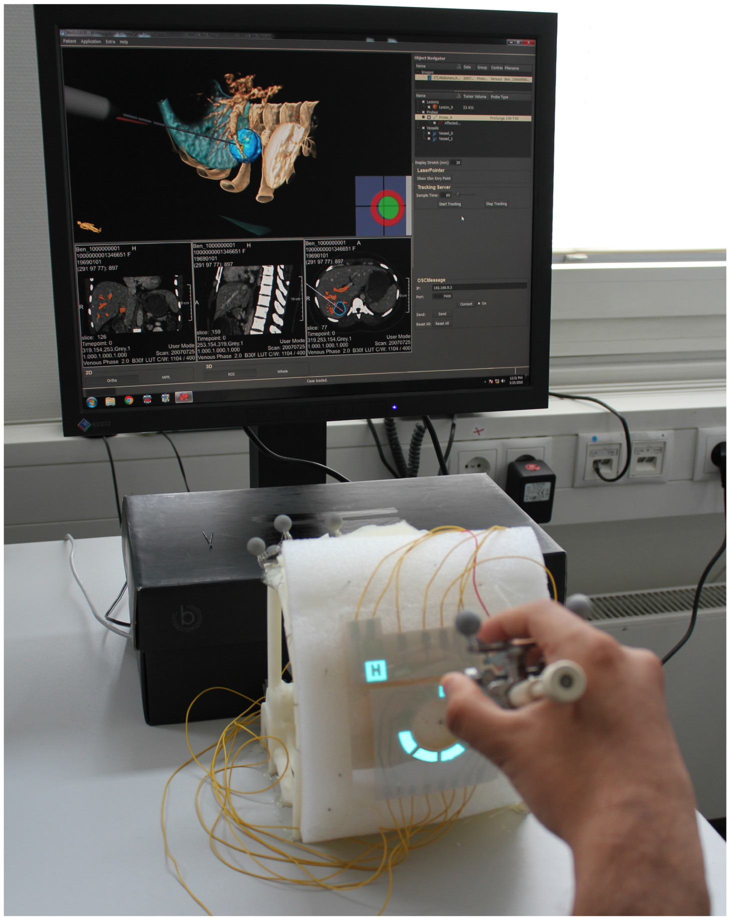

Fig. 1. Picture of our setup with both the standard monitor and the flexible on-body display enabled. The reference navigation application (on the monitor) displays a 3D view of the volume data and several cross sections. Additionally, it provides a cross-hair (small rectangle with blue background) and vertical depth indicator (white bar) for guidance during insertion.

the intersection of human-computer interaction (HCI) and medical research. The specific application domain of the OR requiring robust, efficient, and sterile interaction techniques that do not take attention away from the primary surgery task demands customized solutions.

2.1 Augmented and Mixed Reality for Navigation in Surgery

Among novel approaches to support navigation in surgery are augmented reality (AR) and mixed reality (MR) setups to overlay situs and structures with navigational information. Existing works use different approaches to overlay information such as head-mounted displays (HMDs) [1, 3, 28, 31], microscopes [10], video streams [12, 15], projectors [13, 30], or tablets [27]. In general, AR and MR systems fuse navigational information with the real view of the situs and organs as seen by the operator, reducing the information mapping problem. HMD and projection approaches do not require external monitors and solve the problem of splitting the visual attention. However, HMDs heavily instrument the operator and might be incompatible with other sterile operating equipment or glasses. Projections suffer from difficult lighting conditions inside the OR. Our research extends this body of work on embedded visual navigational information by providing a flexible on-body thin-film display produced by EL screen-printing. In contrast to HMD- and projector-based approaches, our setup does not require the operator to wear an additional device, no additional tracking information is needed, and varying lighting conditions are not a problem. Moreover, our novel display is inexpensive to produce, flexible, and easy to customize.

2.2 Tool-Mounted Displays for Navigation in Surgery

Other researchers have proposed mounting displays directly onto tools and instruments [2, 9, 18, 22] or using mirrors to achieve a similar effect [29]. Herrlich et al. [18], for example, attached a small display directly onto the needle. Results revealed a significant reduction in cognitive load with the same level of performance and the users' preferences for the system, as it reduces the need to switch the focus between the guiding information and the tool itself. Nevertheless, challenges and limitations of needle-mounted displays are the added weight, which influences the balance of the device, the movement of the display when the needle is shifted, and keeping it sterile. Additionally, there is still an offset remaining between the tool-mounted display and the needle entry point. Although this offset is relatively small compared to an external monitor setup, it is still significant compared to the on-body display approach, especially, as the display moves together with the needle. With our approach, we overcome these limitations by integrating the navigation information directly at the entry point where it is needed most. The needle itself is not altered. Hygiene requirements can be met by using sterile covers or by taking novel displays, as these are inexpensive to produce.

2.3 Auditory Display for Navigation in Surgery

Another approach to support navigation in surgery is to integrate auditory displays [6] to reduce reliance on an external monitor. Black et al. [5, 7] and Hansen et al. [14], for example, explored guiding ablation or biopsy needle placement by mapping the distance from the tip of the needle to the insertion point on the skin surface and the handle alignment angle to the correct position to acoustic parameters. Even though early studies enable screen-free needle placement, they also produce evidence of increased cognitive workload when using solely auditory display compared to visual-only or combined audiovisual displays. Moreover, current approaches rely on serializing a navigation task into several sequential subtasks and do not scale well for complex navigational tasks. They also suffer from problems inside a crowded OR. Still, these approaches are promising and may complement our approach in the future.

2.4 EL Displays

EL displays are thin-film segment displays that illuminate dedicated shapes based on electroluminescence. They are robust and inexpensive and are already used in several application areas, such as night lights, billboards, or durable waterproof displays, as they have an average life span of 50,000 hours [33]. Olberding et al. [25] showed how EL displays can be fabricated for highly customizable thin-film touch-displays without industrial equipment by screen-printing the substrate layers. They introduced a comprehensive design space for their use. Because the displays can be printed on various surfaces, they can be used flexibly and with custom shapes, such as on watchbands or plants. In combination with a layer of conductive silver ink [21], these displays can also be used for sensing input. Kao et al. [20] used a similar screen-printing process in combination with conductive silver ink for printing touch sensors on skin, and Weigel et al. [32] produced sensors with integrated illumination. Other application areas of custom displays include data visualization [19], creating ephemeral displays [11], or integrating digital feedback on physical paper [23]. Reinschluessel et al. [26] showed how EL displays can be used in the setting of MRI-guided interventions, where the magnetic field prevents other display technologies from being used. They used the EL display to illuminate preexisting solid needle guidance templates and improved the cognitive load and task time while doing MRI-guided biopsies. The work of Reinschluessel et al. [26] at a basic level uses a similar display technology (EL approach) as we do in this work; however, there are important differences. Reinschluessel et al. do not make use of the flexible properties of the technology. EL technology is used for its other properties and mainly for MRI compatibility. Although both works are related to needle-based interventions, the applications are quite different. The idea of Reinschluessel et al. is very specific to template-guided interventions, whereas our approach is more general. This is also reflected by the completely different visualization approach. In contrast to Reinschluessel et al., we exploit many of the advantages of EL displays for producing a low-cost, custom-shaped, flexible, and lightweight display that also allows inserting a hole for the needle.

3 CUSTOMIZED FLEXIBLE ON-BODY DISPLAY

The goal of our work is to improve navigational guidance for needle-based interventions with respect to two major challenges: information overload and increased task load caused by monitors placed at the periphery.

We address the first challenge by only providing the information that is necessary to successfully carry out the task, such as information about the desired needle insertion point, orientation, and required insertion depth.

We address the second challenge by investigating a suitable display technology that allows us to place the display itself directly into the center of the operator's attention close to the situs.

The solutions to both challenges are not independent, as the underlying display technology constrains what and how information can be presented, and the requirements of information that must be presented will constrain the choice of a suitable display technology. Additionally, there are general safety and hygiene constraints that apply to any physical display technology inside the OR.

Our reference navigation system provides visual guidance for the needle as a cross-hair and a linear depth indicator in addition to rendering the 3D data from different perspectives (Figure 1). Similar visual elements are used in other commercially available systems. The work of Herrlich et al. [18] successfully experimented with employing a similar metaphor on a very small LCD display mounted on an ablation needle. Although mounting the display onto the needle brings it closer to the operator's center of attention, we improve this and investigate whether a display can be placed directly into the field of operation, effectively reducing spatial distance to near zero. Because the needle would have to go through the display, we searched for a technique that would allow us to cut holes into parts of the display so that it would be flexible, lightweight, and easy to manufacture.

Our current prototype is based on the approach for screen-printing EL displays presented by Olberding et al. [25]. This allows us to design custom displays with any vector graphics software, such as Adobe Illustrator or Inkscape. An experienced person can produce such a display within a day and the displays can be printed on flexible and cuttable material, such as special foil or paper, thereby fulfilling our aforementioned requirements.

The basic structure of EL displays is very similar to simple capacitors. It consists of two electrodes separated by a dielectricum and one or several layers of phosphor-based ink. When an alternating current of the right frequency and voltage is applied, the resulting electrical field will stimulate the ink layer to emit photons (i.e., to light up). Naturally, at least one of the electrodes has to be transparent to let the emitted light through. For further details, we refer the reader to the work of Olberding et al. [25].

The benefits of this approach are the quick design and production cycles, physical flexibility, and relatively low costs of approximately 22 € (about $25) per A4-sized display (cf. Olberding et al. [25]). Displays could be produced as relatively inexpensive throw-away components for medical applications, which would make it easier to fulfill hygiene requirements and they could be tailored not only to a general class of interventions, as described in this work, but potentially also to specific patients or personal requirements of physicians.

The drawbacks of this approach are that it is not pixel based, and the number of active segments (i.e., illuminated shapes (cf. Figure 3)), is limited due to the necessary wiring and the manual screen-printing process. Because the displays are based on vectors rather than pixels, the visual elements cannot be changed after production and prohibit use of established metaphors that suit pixel-based monitors (e.g., the aforementioned cross-hair display). The displays are flexible but must not be sharply folded because creasing the printed display results in a break of the printed circuits and destroying the separation of the layers, which is mandatory for them to work.

Inspired by the established cross-hair metaphor (cf. Figure 1) and early work by Herrlich et al. [17], who investigated guiding a needle by LED ring displays attached to the needle's handle, we designed a segmented

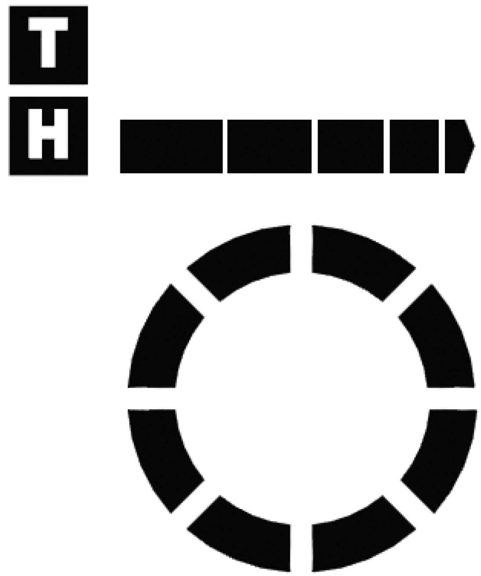

Fig. 2. Schematic of the display elements. The main element is the segmented circle, which provides feedback about the orientation of the needle's tip and handle. The characters T and H indicate if the orientation of tip or handle is currently shown. The display is initialized in mode "T" and then automatically switches between the tip and handle based on which is farther away from the desired orientation. A nonlinear arrow-shaped depth indicator is positioned above the circle and displays the needle's insertion depth with respect to the desired target depth.

circle and a nonlinear segmented depth indicator that are suitable for EL screen-printing (Figure 2). A novel feature of our display is that the circle indicator is placed around a hole for the needle (Figure 3). The needle is inserted through a cutout in the center of the display, and the circle element works very intuitively with the needle in its center. The needle insertion point must be within the diameter of the cutout in the display when placing the display on the situs. However, it is not required to center it perfectly on the insertion point, as the provided navigation feedback is not dependent on the cutout geometry but only on the medical tracking system and planning data.

Our concept decouples achieving the correct orientation of the needle's tip and handle to further reduce information overload and to simplify the display design and implementation. A simple letter-based indicator was integrated into the display (Figures 2 and 3) to signify if the display is currently showing information for the tip or for the handle. The display switches automatically between the two based on which is farther away from the respective target orientation.

The basic needle insertion procedure works as follows. Locate the correct insertion point for the needle's tip inside the circle, using the circle for guidance as described in the following. Bring the tip and handle into alignment with the preset target needle orientation also by using the circle for guidance. Insert the needle until the preset target depth has been reached using the depth indicator for guidance about the depth and relying on the circle indicator to make sure the needle is still correctly aligned while inserting it. This procedure follows the clinical workflow as observed by the authors and reported by consulting physicians.

The circle segments indicate the correct orientation of the needle's tip or handle. If all segments light up, the orientation is correct within the limits of a preset threshold. Unlit segments indicate the direction toward the target orientation. It is also possible to reverse the role of unlit segments—for instance, make the already illuminated segments indicate the direction toward the correct orientation. We explored both design choices

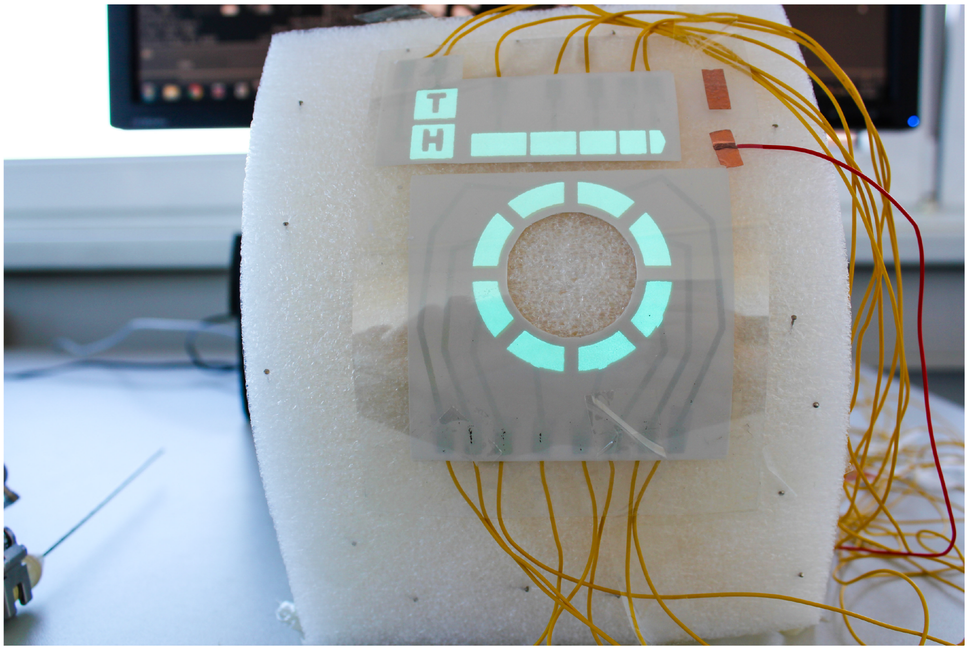

Fig. 3. Picture of our customized flexible on-body display attached to the 3D printed phantom of a human rib cage with all display elements turned on.

in informal pretests, which consisted of informal discussions and testing with our cross-disciplinary team and medical experts from collaborating clinics and found lighting additional segments by moving toward them to be slightly more intuitive and decided to retain this. However, in essence, both alternatives could be used after a short training period.

Our current prototype divides the circle into eight segments. Eight segments strike a design balance between the directional resolution and the complexity of the display. The direction toward the target orientation is indicated by the center point on the arc formed by all currently unlit segments, which are always adjacent to one another. For instance, if only the lower half of the circle is illuminated (i.e., the upper half of the circle is unlit), this indicates a straight up movement. If only a single segment is unlit, this indicates moving toward the center of that segment. If two or more adjacent segments are unlit, this indicates moving toward the center of the arc formed by these segments, and so forth.

Algorithmically, the segments to be turned on or off are determined as follows. The position and orientation of the needle are transformed into a locally defined coordinate system such that x and y represent horizontal and vertical movement of the needle's tip or handle and z represents the insertion depth. This transformation is not specifically performed for our display; it is also needed to display the cross-hair on the standard monitor by the application that drives the normal navigation display output. Feedback about the insertion depth (z-component) is shown by the depth indicator described in the following. The x-y plane is centered on the current target position and divided into rectangular areas (Figure 4). Each area controls a certain set of segments. By determining which area the needle's tip or handle is currently occupying, the respective set of segments is illuminated. For instance, if the needle's handle or tip is currently below the target, the lower half of the circle will be illuminated. We empirically determined how to divide the x-y plane for our prototype during iterative development until we were satisfied with the sensitivity of the response. In an end-user system, this would have to be customized to the physician's personal taste. The current prototype is designed for any needle insertion tasks on the upper

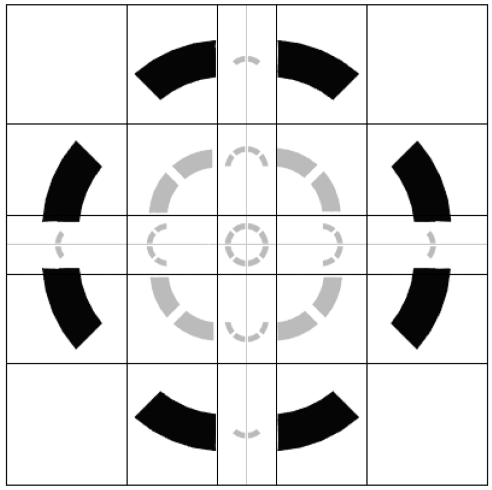

Fig. 4. Schematic showing the subdivision of the x-y plane used to control the respective segments of the circle element of the display. The system determines the location of the needle's tip or handle within the x-y plane and the respective area. Each area is assigned a certain set of circle segments (shown in gray and black), which are then turned on. For instance, if the position falls within the center square, all segments will light up, or if the position is inside the rectangle above the center, all segments of the upper semicircle will light up, and so forth.

body. Affixing displays to other body parts might require adjustments to the display, supporting our choice of an easily customizable base technology.

We designed a nonlinear arrow-shaped depth indicator to provide feedback on the correct insertion depth (Figure 2). It consists of five segments of different sizes to communicate the nonlinearity to the user. When all segments are illuminated, the needle's tip has reached the target insertion depth. We designed a nonlinear version to accommodate for the limited number of segments imposed by the screen-printing approach to provide higher precision close to the target depth, where it is more important, at the cost of lowered depth precision near the insertion point. The overall insertion depth (i.e., the z-distance between the insertion point at the surface and the target position) is calculated and normalized as a percentage value. In our current prototype, we empirically determined the following thresholds to illuminate the segments of the depth indicator: 15% for the first, 45% for the second, 70% for the third, 85% for the fourth, and 100% for the fifth and last segment. This makes the first segment illuminate at a relatively small insertion depth to provide quick feedback to the user to avoid any confusion about the system not reacting. The second and third segment, however, cover a larger range of insertion depth. For the fourth and fifth (last) segments, the depth difference is smaller to provide more accuracy close to the target depth.

The display is connected to an Arduino Mega 2560 microcontroller for switching the segments on and off. The circuit to power and control the display is very similar to the one proposed by Olberding et al. [25] with only small modifications such as additional TRIAC switches for increased stability when using a large number of segments. The Arduino is connected to a PC and communicates with software written in Processing[2] connected via a local network to the navigation system. The navigation system provides the data using the OSC protocol,[3] which are received by the Processing application for output on the display using the Arduino.

[2]https://processing.org/.
[3]Open Sound Control protocol: http://opensoundcontrol.org/.

We used a CAS-One[4] optical medical navigation system. However, we only used the system for tracking and not the CAS navigation software but an application called *SAFIR*[5] developed by Fraunhofer MEVIS specifically for supporting RFA procedures. It provided the test environment for our studies (Figure 1). The SAFIR application presents a 3D view, 2D cross sections, and a 2D cross-hair guide similar to state-of-the-art systems.

The current prototype is hardwired to the Arduino, which is connected via USB to the computer. For the next iteration and for usage in the OR, we plan to replace the current model with a microcontroller capable of wireless connection and to power the display with a battery. The display itself will be covered with a sterile foil.

4 EVALUATION

We planned and conducted an empirical evaluation to compare the flexible on-body display against using a standard monitor setup and a combination of both. We hypothesized that using the flexible display would

(H1) allow successfully and reliably placing the needle,
(H2) reduce overall task load,
(H3) reduce the time spent looking on the monitor,
(H4) improve overall usability, and
(H5) improve task time while maintaining accuracy,

4.1 Setup

We used a 3D-printed phantom of a liver including ribs, vessels, and a tumor extracted from a contrast-enhanced CT dataset for the evaluation (Figure 5). The phantom was affixed on a table in front of the participants (Figure 6). Two layers of foam attached to the phantom provided cover and tactile resistance. The on-body flexible display was attached to the outer layer of foam and turned off when not in use. The Arduino and all electronic components for the display were hidden in a small black box behind the phantom. The outer layer of foam and the flexible display were repositioned for each participant to avoid giving away any hints by existing piercing points. The tracking unit of the navigation system was placed on the right side and the monitor was placed in front of the participants on the table on top of the black box directly behind the phantom (Figure 6). The monitor was turned off when not in use. Placing the monitor directly in front slightly favors the control condition compared to the clinical situation in which the monitor is usually farther away or placed slightly to the side of the surgeon. However, we wanted to be sure to not bias the situation in favor of the flexible display.

We were careful to explain the task in terms appropriate for participants coming from a nonmedical background and only proceeded after a participant confirmed that he or she had understood the task. Participants were asked to sit at the table in a comfortable position and grasp the needle with their dominant hand. We placed a video camera in front of the participant to analyze the attention distribution between the flexible display and the monitor (only C3). The task consisted of placing the needle at the correct entry point and inserting it at the correct angle up to the correct depth. The participants were instructed to pay attention to the correct orientation while inserting the needle and to use the navigation information to place the tip of the needle at the center of the tumor.

4.2 Procedure

We employed a within-subjects design, and conditions differed only in the way the navigational information was presented:

(C1) only on the flexible display,
(C2) only on a monitor, or
(C3) simultaneously on the flexible display and a monitor.

[4]CAScination AG, Switzerland.
[5]Software Assistant for Interventional Radiology.

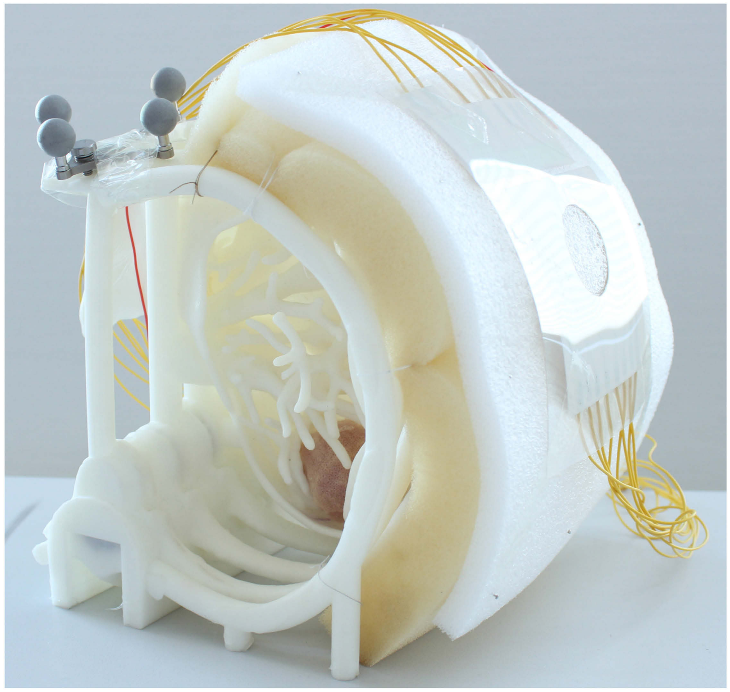

Fig. 5. Picture of the interior of the 3D-printed phantom of a section of human rib cage with liver vessels. A tumor is recreated with a piece of colored foam. Two layers of different types of foam cover the phantom and provide resistance for the needle.

The order of conditions was pseudo-randomized across participants using a Latin-square scheme to counterbalance for potential learning effects. After a short welcome and introduction, participants were asked for their informed consent and we collected demographic data and relevant experience. For each condition, participants trained the task at least once without recording any data until they felt confident enough to proceed. They performed the task once for each condition. They were given a maximum time limit of 3 minutes to complete the task, which was otherwise considered complete when the participants announced that they thought they had reached the best position according to the navigational information.

We recorded task completion time and accuracy—that is, the final distance (in internal units as provided by the navigation system) between the needle's tip and the target location. The participants completed a short questionnaire after each condition and an additional short questionnaire after completing all conditions, described in the following. Participants were informed that they could and should ask for a break if needed; however, the short breaks while filling out the questionnaires and the instructor preparing the next condition provided some time for resting, and no participant asked for an additional break. A complete session (all three conditions) took an average of 40 minutes.

The questionnaire distributed after each condition consisted of the NASA-TLX [16] for measuring task load and the System Usability Scale (SUS) [8] for measuring overall usability. We added a custom question asking for overall preference on a 5-point Likert scale. The additional questionnaire distributed after all conditions consisted of two open qualitative questions asking for general positive and negative comments, as well as a question asking the participant to assign an overall rank to all three conditions from 1 (best) to 3 (worst). Using post-experimental video analysis, we manually measured the time percentages of participants looking at the flexible display versus the monitor during C3.

Fig. 6. Overview of the evaluation setup. The phantom is fixed on a table with a black box behind it that hides the controlling electronics and a computer monitor on top. The scene is tracked from above with an optical medical tracking system.

4.3 Participants

We recruited volunteers through handouts, on-campus flyers, and emails to university mailing lists. We offered no monetary compensation but provided sweets and soft drinks during and after the experiment. Overall, 30 volunteers (12 female and 18 male) participated in our evaluation. All were students or researchers from different departments with only one exception of a participant who was employed outside the university. One participant was left handed, and 29 were right handed. No participant indicated any physical disorder. Seventeen volunteers suffered from mild viewing impairments (e.g., short sightedness) and performed the experiment while wearing their glasses or contact lenses. Four participants indicated regular use of 3D applications (e.g., 3D modeling

Table 1. Mean ± Standard Deviation Across Conditions for Task Load (NASA-TLX; [0, 100]; Lower Is Better), Usability (SUS; [0, 100]; Higher Is Better), Overall Rating (Custom; 5-Point Likert Scale; Higher Is Better), Task Completion Time (Seconds; Lower Is Better), and Accuracy (Distance of Tip to Target; Internal Units; Lower Is Better)

	Condition		
Measure	*On-Body Display (C1)*	*Monitor (C2)*	*Both (C3)*
Task load	24.63 ± 12.92	37.47 ± 13.97	27.61 ± 10.68
Usability	85.80 ± 13.51	70.09 ± 19.48	81.43 ± 13.31
Rating	4.39 ± 0.79	3.86 ± 0.89	4.50 ± 0.64
Task time	23.51 ± 10.49	30.09 ± 17.42	32.37 ± 15.02
Accuracy	39.50 ± 08.85	22.97 ± 10.97	36.05 ± 11.68

software). No participant had any prior experience with medical navigation systems. All participants successfully finished all tasks under all conditions within the time limit of 3 minutes.

4.4 Data Processing

We conducted a one-way repeated-measures analysis of variances (RM-ANOVA) for all measures except for the ranking. We used Mauchly's test to check the RM-ANOVA precondition of sphericity. In cases that violated the sphericity assumption, we reported the Greenhouse-Geisser corrected results. If indicated by significant results of the RM-ANOVA, we used Sidak-corrected t-tests for dependent groups to do a full set of pairwise post hoc comparisons. We used the statistical package SPSS (v24), which factors the Sidak correction directly into the p-value, which therefore should be compared against the uncorrected alpha level of 0.05 to check for statistical significance. We conducted a nonparametric Friedman test for the ranking and Bonferroni-corrected Wilcoxon tests for dependent groups for pairwise post hoc comparisons. For consistency with other measures, Bonferroni correction was performed by multiplying the p-value instead of dividing the alpha level.

5 RESULTS

Due to calibration problems during the experiment, we had to exclude one participant from all further analysis. One participant did not answer the SUS questionnaire and thus was not considered for calculating the usability score. Additionally, two participants had to be removed from the time and accuracy calculations, one because of a corrupted log file and the other had unknown problems during C2 (i.e., the completion time was more than three standard deviations above the mean).

5.1 Quantitative Results

The means and standard deviations for task load (NASA-TLX), usability (SUS), overall rating, task completion time, and accuracy are summarized in Table 1.

Task load was calculated as the overall task load index according to the NASA-TLX questionnaire, which results in an overall score ranging between 0 (best) and 100 (worst). Usability is reported as the overall score according to the SUS questionnaire, resulting in a score ranging between 0 (worst) and 100 (best). Overall rating was calculated as the result of a custom question rated on a 5-point Likert scale, where higher indicates better.

In the conclusive ranking after all conditions, C3 was ranked best (Mdn = 1.5), C1 second best (Mdn = 2.0), and C2 was ranked worst (Mdn = 3.0), which is consistent with the overall rating results. However, only the differences between C1 and C2 and C2 and C3 were statistically significant (see the following).

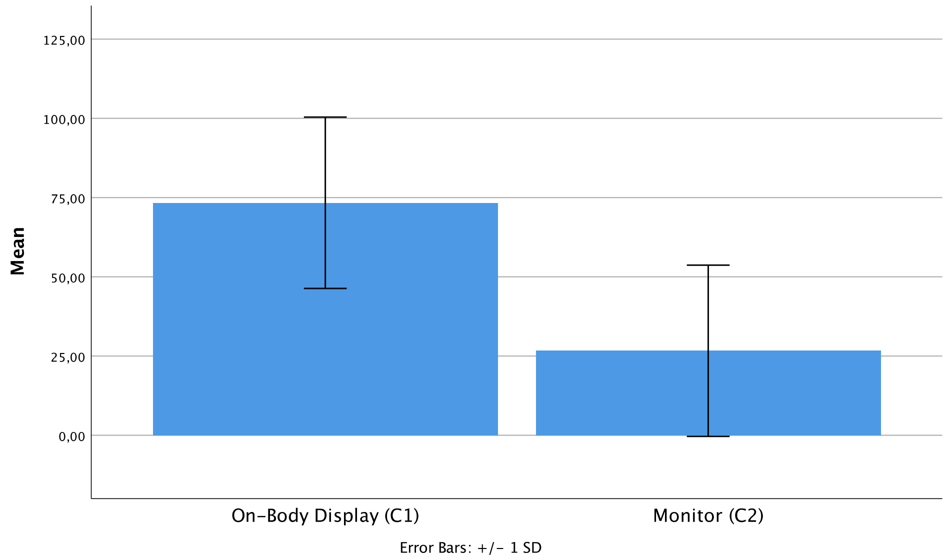

Fig. 7. Means and standard deviations for average normalized view percentage (only C3).

Mauchly's test did not show a violation of sphericity (W(2) = 0.931, p = 0.383) for task load. RM-ANOVA revealed a highly significant difference across all conditions (F(2,56) = 12.266, $p < 0.001$, partial $\eta^2 = 0.305$). Pairwise comparison revealed a highly significant difference between C1 and C2 ($p < 0.001$) and C2 and C3 ($p = 0.005$) but no significant difference between C1 and C3.

For usability, Mauchly's test revealed a violation of sphericity (W(2) = 0.448, p < 0.001). RM-ANOVA with Greenhouse-Geisser correction ($\epsilon = 0.644$) revealed a highly significant difference across all conditions (F(1.289,34.790) = 11.233, $p = 0.001$, partial $\eta^2 = 0.294$). Pairwise comparison revealed a highly significant difference between C1 and C2 ($p = 0.003$) and C2 and C3 ($p = 0.016$), and a trend ($p = 0.067$) for a difference between C1 and C3.

Mauchly's test did not show a violation of sphericity (W(2) = 0.830, p = 0.089) for overall rating. RM-ANOVA revealed a highly significant difference across all conditions (F(2,54) = 8.957, $p < 0.001$, partial $\eta^2 = 0.249$). Pairwise comparison revealed a significant difference between C1 and C2 ($p = 0.025$) and a highly significant difference between C2 and C3 ($p = 0.002$) but no significant difference between C1 and C3.

For task completion time, Mauchly's test did not show a violation of sphericity (W(2) = 0.965, p = 0.638). RM-ANOVA revealed a significant difference across all conditions (F(2,52) = 3.492, $p = 0.038$, partial $\eta^2 = 0.118$). Pairwise comparisons revealed a significant difference between C1 and C3 ($p = 0.035$) but no significant differences between C1 and C2 or C2 and C3.

Mauchly's test did not show a violation of sphericity (W(2) = 0.977, p = 0.747) for accuracy. RM-ANOVA revealed a highly significant difference across all conditions (F(2,52) = 22.358, $p < 0.001$, partial $\eta^2 = 0.462$). Pairwise comparisons revealed a highly significant difference between C1 and C2 ($p < 0.001$) and C2 and C3 ($p < 0.001$) but no significant difference between C1 and C3.

A one-sample t-test against the 50% level (assumed equal view distribution) for the average normalized view percentage (cf. Figure 7) measured in C3 for the flexible display (M = 73.344, SD = 27.021), and the monitor (M = 26.656, SD = 27.021) revealed a highly significant difference ($t(28) = -4.652$, $p < 0.001$).

A Friedman test for ranking revealed a highly significant difference across all conditions ($\chi^2(2) = 12.214$, $p = 0.002$). Pairwise comparison revealed a highly significant difference between C1 and C2 ($Z = -2.923$, $p = 0.009$) and C2 and C3 ($Z = -3.016$, $p = 0.009$) but no significant difference between C1 and C3.

5.2 Qualitative Feedback

The reception of the flexible display was generally very positive. Participants remarked positively that it allowed focusing on the display and the patient, the visualization was quite intuitive, the display was easy to use, and they liked the compact and focused design. They critically remarked about the lack of accuracy and the missing visualization of the organs and bones of the patient.

Although participants remarked positively on the better accuracy of the standard monitor setup and being able to see renderings of the 3D image data together with the needle from different perspectives, they noticed that it was difficult or took additional effort to move the needle carefully and correctly while looking at the monitor.

The combined setup was received differently by the participants. Some remarked about the positive aspect of having the choice to use what they liked best and being able to use the monitor to double check the needle's position if they felt unsure; however, others found that having two different options to increase the complexity and the need to constantly switch between them as an additional source of distraction.

6 DISCUSSION

All participants successfully finished all tasks in approximately 30 seconds on average over all conditions well within the time limit of 3 minutes. However, accuracy was significantly lower with an increase in distance of about 72% for C1 and 57% for C3 compared to C2, which is a difference of approximately ±1 cm.[6] Although we admit that this is in fact a significant increase that needs to be addressed with a high priority in future work, the participants were still able to successfully and reliably place the needle well within the tumor in C1, which had the lowest standard deviation of all conditions for accuracy, and thus confirmed H1. Under clinical conditions, this decrease in accuracy would certainly be problematic for some interventions.

From our observations, the decrease in accuracy could be related to the limited number of circle segments and the preset thresholds for controlling them. The discretization in the form of the segmented circles and depth indicator segments requires to assign empirically determined thresholds to balance how to map real-world distances to the number of segments. For instance, will segments change if the needle's position changes by 10 cm or by 1 cm? In a clinical setting, this could be configurable or even dynamic. A fixed balance like we chose might therefore affect accuracy. We empirically determined these mappings (thresholds) based on informal pretests. For the next iteration, we plan to at least double the number of segments and experiment with different or even dynamically adaptable thresholds. Qualitative feedback is consistent with the quantitative results. However, although some participants remarked that they used the monitor to double check the needle's placement in C3, the results from C3 are very close to C1 and significantly different from C2, which means that in fact the performance of the on-body flexible display dominated C3, which is consistent with our expectations (cf. H3 in the following).

Our results clearly confirm H2. For C1 and C3, which both included the flexible display, task load was significantly reduced compared to C2. Qualitative feedback seems to indicate that for some people a second display (as in C3) might actually increase the task load; however, we could not observe this effect in the quantitative data of our study.

We can also clearly confirm H3. The manually measured[7] differences for the normalized percentages of the time spent looking on the monitor versus the on-body display during C3 were highly significant. It must be noted that the time spent looking on the flexible display might be partly attributed to also looking at the phantom and the needle while performing the needle insertion task. However, all other measures (positively and negatively) are generally comparable between C1 and C3, but significantly different from C2, which strongly supports the

[6]Unfortunately, we cannot directly calculate the physical distance from the navigation system's internal units, so this is a rough estimation from our observations.

[7]By post-experimental video analysis.

results of the video analysis. This also has strong implications for introducing such a technology into the OR, as for good or bad the on-body display dominates the overall results, which is an important finding.

H4 is clearly confirmed by our results. The SUS scores, the overall rating, and the conclusive ranking are all significantly different in favor of C1 and C3. Qualitative feedback is consistent with this finding with participants explicitly remarking positively on the intuitiveness of the flexible display.

For the current prototype, we must partly reject H5. Although task time is indeed significantly improved for the flexible display, at the same time accuracy is significantly decreased. We mainly attribute the limited accuracy to the limited number of segments and maybe to lenient preset thresholds. Further, we believe that task time and accuracy are related in this case because a more forgiving flexible display with respect to the needle's orientation will naturally speed up the process of finding the *correct* orientation. We strove for a balance between design complexity and performance, and speed is an important factor in medical procedures, as patients benefit from shorter procedures. However, we expect improvements regarding task completion time also for future iterations with improved accuracy as a result of allowing the operator to focus more on inserting the needle and taking less time for checking the monitor. Future studies are required to confirm or reject this hypothesis.

Overall, we could largely confirm the expected benefits of the display and also identify future directions for improvements and research. It should also be noted that the approach is not limited to RFA. Our current display concept should be usable for other needle-based approaches, and the general concept of flexible on-body displays is even more general. The easy and fast customization allows to produce displays that are personalized for specific patients (e.g., the scales and visual elements could be optimized for a specific disease) or for the specific requirements of the operator. For instance, the arrangement of the visual elements could be adjusted to personal preference, handedness, language, and so forth.

A limitation of our results regarding a direct use inside the OR is conducting the experiment with medical novices. Nevertheless, experts were involved in the pretests and the team of authors is cross disciplinary (including a radiologist as a domain expert). Parts of the setup (e.g., the phantom) are based on previous work involving domain experts and surgeons. In the future, we plan to do an evaluation with physicians. However, we consider this a second step, and we believe that it would not have been practical nor ethical (with respect to their limited availability) to invite physicians without a first general study to prove our concept. The evaluation was designed and explained to the participants in a way that requires no prior medical experience and without the potential bias of in-depth knowledge and experience of existing medical navigation systems. Therefore, we could focus the evaluation on investigating if and how well the basic approach works, which is basically a hand-eye coordination task.

7 CONCLUSION AND FUTURE WORK

In this article, we presented the concept and prototype of custom flexible on-body thin-film displays for guiding needle-based interventions. Our work addresses two relevant issues of current medical navigation systems: information overload and uncomfortably placed monitors for providing the visual feedback.

Based on the requirements and constraints within the OR, screen-printed EL displays provide a good balance between manufacturing complexity, cost, and the desired properties, such as being able to print them on flexible and cuttable foil or paper. We developed a custom visualization metaphor in the form of a segmented circle and a nonlinear depth indicator suitable for vector-based displays.

We summarize the main contributions of this work as the novel application of screen-printed EL displays to medical navigation including a concept and prototype for an on-body display for guiding needle-based interventions and empirical results from an evaluation comparing the on-body display approach to a standard monitor navigation setup and a combined condition including both.

Our results show that the on-body display allows users to successfully and reliably carry out needle-based navigation tasks while significantly lowering task load and improving overall usability compared to using a standard monitor setup. All participants preferred the on-body display and the combined condition to using the standard monitor setup. Additionally, during our evaluation, the on-body display significantly reduced task completion time, although at the cost of significantly decreasing accuracy as well.

We hypothesize that this effect is caused by the limited number of circle segments and nonoptimal thresholds of the current prototype and is not a principal limitation of the approach. By analyzing the combined condition, we found that the on-body display is the dominating source for visual feedback if both types of displays are available.

We plan to experiment with an increased number of segments to address the current issues regarding accuracy and to find the optimal balance between display complexity and navigation accuracy. We will also optimize the used thresholds and investigate adaptable dynamic thresholds for providing the best accuracy near the target location.

After providing the general proof of concept in this work, we plan to evaluate the concept stepwise in more and more realistic settings under OR conditions and with experienced physicians.

We will also investigate applying the technology to other medical areas, starting with different needle-based interventions but also completely different types of procedures that make use of medical navigation. We will explore the potential benefits of customizing the displays to a specific patient and/or the personal requirements and preferences of the physician carrying out the procedure.

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