User Centric Device Registration for Streamlined Workflows in Surgical Navigation Systems

Paul Thienphrapa, Prasad Vagdargi, Alvin Chen, and Douglas Stanton

Abstract— **Alongside sweeping transformations in healthcare, a timeless drive to make surgical interventions less invasive and more effective has led to the integration of disparate technologies into surgical navigation systems. Fusions of device tracking and medical imaging modalities have been comprehensively investigated for opportunities to improve care. Such composite systems provide more and better information, enabling clinicians to operate less invasively and more effectively. Because of these merits, the preoperative ritual of harmonizing multiple information sources has been tacitly adopted.**

In this paper, we challenge the paradigm of *preoperative registration*. Proposed herein is a technique in which a clinician registers an interventional device to a navigation system simply by gesturing the device through a strategically designed fixture. In the background, the system continuously monitors the device path for this registration gesture. We demonstrate generality by applying the method to both robotic and electromagnetically tracked devices, and exhibit versatility by repeating the registration at multiple device base locations. Experiments indicate sub-millimeter accuracy versus conventional approaches on the same setup. Consequently, clinicians can register devices on the fly, increasing flexibility in setup and redefining workflow possibilities in surgery.

I. INTRODUCTION

Surgical and interventional systems are in the midst of a revolution. Healthcare is witnessing a gradual transition from traditional freehand procedures to smart guidance and robotics. This progression can be found in the history of bronchoscopy [1], which was invented in its modern form in 1964 [2] to enable inspection and intervention in the airways. In 1992, endobronchial ultrasound (EBUS) was incorporated to visualize tissue beyond the airways [3]. Electromagnetic (EM) navigation was subsequently integrated to improve localization of targets with respect to preoperative CT; the year 2006 played host to the first human trials [4]. By 2018, robotic bronchoscopy had been performed in a human [5] using the Monarch Platform [6].

Increasing capability begets complexity. In the example above, clinicians learned how to interpret ultrasound images in the EBUS era, register devices to CT in the EM navigation era, and register robots to anatomical roadmaps in contemporary times. These burgeoning technical skills rest atop specialized medical training, so growing complexity, while well intentioned, can induce workflow inefficiencies and even occasional errors. For the remainder of this section, we take a step back in order to understand the broader influences that, despite these challenges, tend to increase complexity in surgical navigation.

A. Clinical Trends

Value-based healthcare [7] persists despite challenges in its implementation, fueled by economic pressure on patients and providers. Improved outcomes, patient satisfaction, and operational efficiency have thus become focal points. A byproduct of these movements is the growth of minimally invasive approaches to surgical interventions; increasingly skilled and complex procedures have been enabled and improved by modernization. Efforts have thus been directed towards incorporating robotics, optical tracking, EM tracking, and image fusion, among others, into integrated solutions. GE Innova IGS 530, Philips EchoNavigator, and Siemens Artis zeego comprise a small cross section of solutions emerging in response to needs in interventional cardiology. Meanwhile, initiatives such as the US Food and Drug Administration (FDA) workshop on surgical robotics [8], standardization of medical robot autonomy [9], and FDA approval of artificial intelligence to detect eye disease [10] are refining the regulatory pathway for continued innovation.

B. Technological Trends

EM and optical tracking systems are mature technologies in ubiquitous use, culminating in their integration into commercial navigation systems such as (respectively) Medtronic superDimension for bronchoscopy and Stryker NAV3 for orthopedics. Universal Robots, KUKA, and a host of other robotics companies now offer platforms for non-industrial and, increasingly, medical integration. Auris Health exemplifies this development—its Monarch Platform comprises two customized manipulators from Kinova [11]. A growing collection of open source toolkits allows one to draw from an extensive selection of technologies and compose sophisticated prototypes. The prospects of surgical navigation are further enhanced by artificial intelligence, which for surgery is a nascent specialty promising to augment perception and cognition [12].

C. Commercial Trends

Activity in the private sector has had an indirect yet palpable impact on the evolution of surgical navigation. For example, in the context of its medical imaging systems, Philips acquired Volcano and its intravascular ultrasound catheters, reflecting a broader phenomenon of combining information

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and treatment capabilities. Later in 2015, Ethicon and Verily formed Verb Surgical to collaborate on digital innovations in surgery; Ethicon would solidify its robotics presence by acquiring Auris Health in early 2019. In 2016, Medtronic partnered with (and later acquired) robotics firm Mazor to forge a new solution for spinal implants. Abbot acquired like-entity St. Jude Medical in a $25B USD transaction, a fraction of the $332B USD in healthcare mergers of 2017 [13], populated mainly by shifts in hospital and insurance enterprises. In 2018, Amazon, J.P. Morgan, and Berkshire Hathaway introduced themselves into the industry through a joint healthcare venture, headlining a set of non-traditional, high profile alliances that would follow. While the circumstances surrounding these events vary, the tendency towards consolidation foretells increasing integration of capabilities that were previously decoupled.

D. Broader Trends

The commercial success of Intuitive Surgical's da Vinci Surgical System has had a notable influence on the adoption of advanced surgical technologies. More recently, consumer products featuring smart voice control and connectivity have spurred breakthroughs in overall technological engagement. With social momentum stemming from digitization and personalization, what was once a willingness to adopt innovation is accelerating into an expectation.

E. Integration

Evolution in surgical systems can be understood as a confluence of these trends, and a theme that threads them all is integration. *Advantageous* integration would be those that support key clinical needs: improved outcomes, patient satisfaction, and operational efficiency. In the context of surgical navigation, systems should be *configurable* to accommodate variances in patient presentation, yet *simple to configure* for any of these variances. Registration for surgical navigation has been thoroughly investigated, based on practices of times past. Given emerging trends, however, the convention warrants reexamination of what was a known art a generation ago. In the following section, we provide some background on existing registration approaches before detailing our proposed method.

II. BACKGROUND

Clinicians A and B, users of a navigation system, agree to perform a registration task. Clinician A activates a special mode in the software. Clinician B, using the tracked device, locates the first landmark in the surgical space. She touches the device to the landmark, and signals as much to Clinician A. Manning the computer console, Clinician A enters this event into the software before notifying Clinician B of the same. The process repeats itself in this manner until all three or more ordered landmarks have been visited. The software computes the spatial transformation between the device and a virtual workspace. The intervention can proceed unless—or until—the calibration is perturbed, whereupon Clinicians A and B agree to start over.

This canonical registration scenario has recycled itself through many research labs, where the ample technical expertise can help mitigate the minutiae. After all, the benefits of navigation should justify these cognitive and operational overheads. In clinical settings, however, the sequence may be experienced as arcane. Registration is indeed widely regarded as cumbersome, particularly with artificial fiducials [14]. The rationalization of benefits continues to falter amidst trade terms such as Flash Registration from 7D Surgical and Universal Automatic Image Registration from Brainlab promising to alleviate the technical pain. The latter also offers Z-touch [15], comparable to the Medtronic Fazer [16]: the clinician scans the anatomy with a laser, and the digitized reflections are matched to a skull model.

Early stage investigations have likewise acknowledged the prohibitive nature of registration. Automatic registration was proposed for neurosurgery in [17]. Bimodal fiducials were attached to the patient's skull prior to cone beam CT imaging. Intraoperatively, the fiducials were localized in both the image and with an optical tracker, allowing the image to maintain alignment with the moving anatomy. Ref. [18] presented an automatic method for bronchoscopy. Airways were segmented from a lung CT image and abstracted into a tree representation. An EM tracked bronchoscope was then navigated blindly down the trachea. Registration between the bronchoscope position and CT image was refined based on its likeliest position on the bronchial map. Historically, calibration activities in robotic surgery have centered around improving accuracy in neurosurgery [19]–[21], orthopedics [22]–[24], and laparoscopy [25]–[27]; in the latter case, [28], [29] progress towards automated techniques.

III. METHODS

A. Contributions

Technologies emerge, circumstances evolve, and research efforts advance, yet one element continues to elude progress in navigation systems: registration of tracked devices. We herein propose a streamlined strategy for registering devices in surgical navigation systems. An operator passes the device through a special fixture. A background monitor detects this event, and registration is complete.

We submit, universally, that clinical users can be liberated from the technicalities of registration. Given explicit initiation of the task through a single simple gesture, clinicians maintain cognizance over the workflow. Our approach is embedded into the clinical setup and is carried out deterministically, as compared to random scanning using a separate laser [15], [16]. We work towards a solution that is free of patient-mounted fiducials, such as the bimodal fiducials [17] described above whose placement is a substantial workflow disruption. Foregoing the uncertainties of an iterative registration [18], our approach overcomes the aforementioned drawbacks of prevailing registration paradigms. Detailed below is a new blueprint for registration, an intuitive interface to complex systems operating in clinical environments.

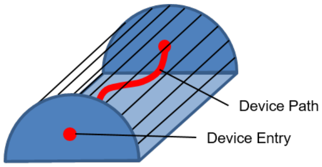


Fig. 1. Example registration fixture containing a special path for the device to traverse, suitable for a flexible EM tracked catheter.

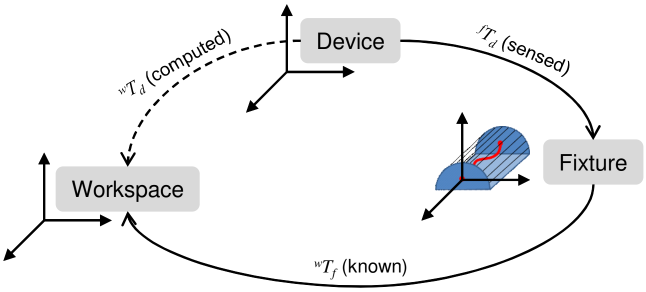


Fig. 2. Coordinate transforms in the proposed technique. The workspace may refer to the patient (not pictured), provided the fixture is anatomically attached. Alternatively, the transform between the workspace and the patient can be obtained intraoperatively using established methods.

B. Overview

To the clinician, registration using the proposed technique is achieved by inserting the tracked device through a fixture (Fig. 1) mounted in the workspace (e.g., patient table). Fig. 2 illustrates the underlying coordinate transforms:

- $^{w}T_{f}$: Fixture frame f in workspace w is by design;
- $^{f}T_{d}$: Device frame d relative to the fixture emerges once the monitor detects the known path in the fixture; and
- $^{w}T_{d} = {^{w}T_{f}} \times {^{f}T_{d}}$ is the device-to-workspace registration, immediately computed upon fixture traversal.

The supporting system process is captured in Fig. 3. As the device traverses the fixture, a background monitor accumulates tracked positions, searching for a traversed path that matches the expected fixture path. By crafting a fixture and mounting it in the workspace in a predetermined manner, we embed the technical burden of registration into the system design and away from end users.

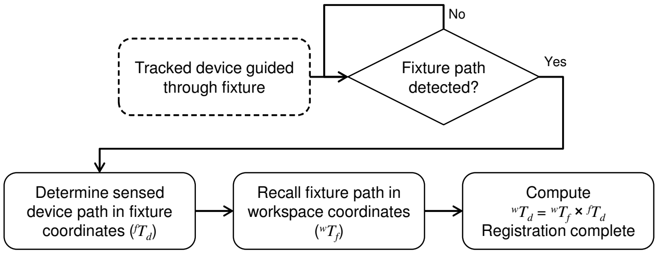


Fig. 3. Underlying process for the streamlined registration technique. Device position is continuously monitored, and registration is triggered only when the known path is detected.

C. Tracking the Patient Anatomy

A navigation system may accommodate incidental patient motion by registering and tracking the pertinent anatomy. An example is in a cardiac catheterization lab, where the patient table is encoded with respect to the C-arm. Fluoroscopy, rather than fiducials, can then be used to track the patient [30], [31] so that the transform $^{p}T_{w}$ from the workspace (table) to patient frame p is known intraoperatively. Attaching the fixture of Fig. 1 to the table then permits the device to be registered to the patient as $^{p}T_{d} = {^{p}T_{w}} \times {^{w}T_{d}}$, where $^{w}T_{d}$ is computed as above.

This represents a clinical scenario in which the assumption of a known fixture-to-workspace relationship $^{w}T_{f}$ (see Fig. 2) is adequate, so we defer consideration of the patient frame. Less preferably, mounting the fixture onto the patient equates the patient with the workspace ($^{p}T_{w} = I$, so $^{p}T_{d} = {^{w}T_{d}}$). In yet other setups, optical tracking can substitute for the role that fluoroscopy plays above. In other words, we can account for patient motion through established means; so for the sake of clarity, we generalize our definition of *workspace*—it may equivalently refer to the table or patient frame.

D. Path Monitoring

The utility of our registration method thus hinges upon the device-to-fixture transformation $^{f}T_{d}$. As the clinician manipulates the tracked device, a background process (Fig. 3) scans the trajectories for the fixture path. Once detected, the path is transformed into the fixture frame. This workflow allows the clinician to perform registration on demand and away from the console. The path should be distinct from incidental use to avoid inadvertent triggering; the system may also offer convenient means of confirming user intent.

In practice, the fixture path search space can be limited to the most recently acquired $N = f_s \times \left(t_f + \Delta t_f + t_d\right)$ position samples, where f_s is the sampling rate, t_f is the time for the device to transit the registration fixture, Δt_f accommodates variabilities in that estimate, and t_d is an extra delay between the travel and the result. These quantities can be tuned to the use case. For our fixture (Fig. 4, *top*), we provision $t_f = 2$, $\Delta t_f = 1$, and $t_d = 1$ seconds. A sampling rate $f_s = 30$ Hz then yields $N = 120$ samples.

Given a set of device positions $\mathbf{P} = \left\{p_i \in \mathbb{R}^3 | 1 \leq i \leq N\right\}$, the problem is to determine whether some $\mathbf{Q} \subseteq \mathbf{P}$ matches a model, and if so, find the rigid transformation $^{f}T_{d}$ mapping $\mathbf{Q}$ in device space to fixture model space. For this problem, a multitude of solutions is available in the literature. Should the model also be represented as a set of points, methods such as iterative closest point (ICP) [32], its advancements (e.g., [33]–[35]), coherent point drift [36], and cross correlation may be used. Alternatively, the model may be designed as a function to which $\mathbf{Q}$ is fit using a polynomial, B-splines [37], NURBS [38], Levenberg-Marquardt [39], etc. The present framework is agnostic to the algorithms used; such decisions would ultimately be driven by requirements. In that regard, we exploit properties of our design to reduce the problem to a sequence of intermediate calculations:

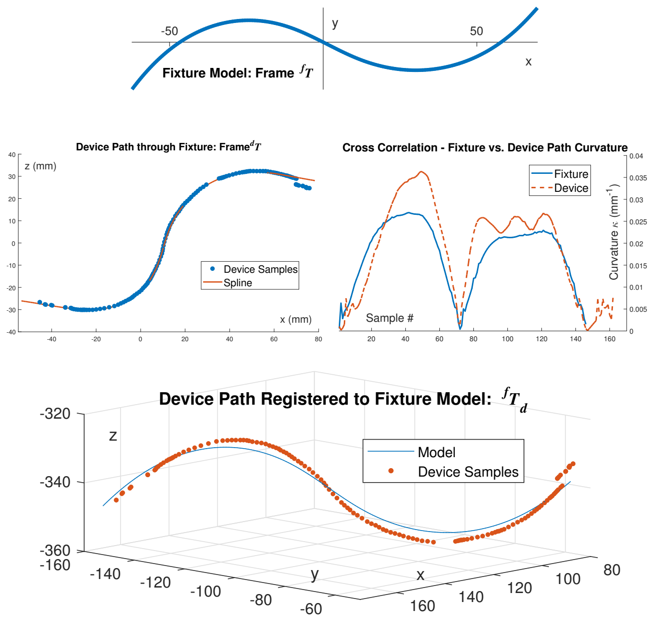


Fig. 4. Path monitoring approach for computing device-to-fixture transformation ^fT_d. (*Top*) Fixture path model, an asymmetric, planar curve with coordinate frame ^fT defined using PCA. (*Mid-left*) Position samples through the fixture with spline smoothing. (*Mid-right*) Cross correlation is performed between the *curvature* of the model and device spline to find $\mathbf{Q}$, upon which PCA is used to compute device path frame ^dT. (*Bottom*) Result of applying ^fT_d, approximated from $^fT \times {}^dT^{-1}$ and refined using ICP.

1) Generate a sequence $\mathbf{R}$ by spline smoothing $\mathbf{P}$ and resampling with equidistant spacing (Fig. 4, *mid-left*)
2) Compute curvature $\kappa_i = \|r_{i+1} - 2r_i + r_{i-1}\| \, \forall r_i \in \mathbf{R}$
3) Perform cross correlation between the κ_i and its model counterpart to identify pertinent path points $\mathbf{Q} \subseteq \mathbf{P}$ (Fig. 4, *mid-right*)

Reducing $\mathbf{P}$ to a 1D signal potentially introduces ambiguities, but these can be overcome (see Sec. IV-D) to enable immediate computation on modest hardware. Provided a correlation is found, the algorithm continues:

4) a. Retrieve ^fT, the local frame of the fixture model
   b. Compute ^dT from the principal components of $\mathbf{Q}$
5) Approximate the transform as $^fT_d = {}^fT \times {}^dT^{-1}$ and then refine using ICP (Fig. 4, *bottom*)

While device position is continuously monitored, the result is applied only if the fiducial registration error (FRE) is low enough to suggest that the clinician has indeed executed the registration task. Otherwise, the result is passively ignored. An alternative to the local fixture frames of Step 4 could be predefined curve segments detected as discrete features for landmark registration. Indeed, the design possibilities are innumerable, as discussed in Sec. IV-D. For the present study, we favored a design that reduced complexity in both mechanical and computational terms, facilitating ease of use and real-time processing.

E. *Impact*

The simplicity of the proposed method belies a broader shift from a system centric to a clinician focused mindset, highlighting opportunities for intuitive, non-disruptive interfaces for workflow simplicity amidst increasing complexity overall. Within a minimal footprint, it can help clinicians register devices more consistently and re-register more conveniently (e.g., when an EM field generator is displaced). Enabling greater versatility in procedure setup, it can enhance the realized efficacy, and eventual permeation, of integrated solutions.

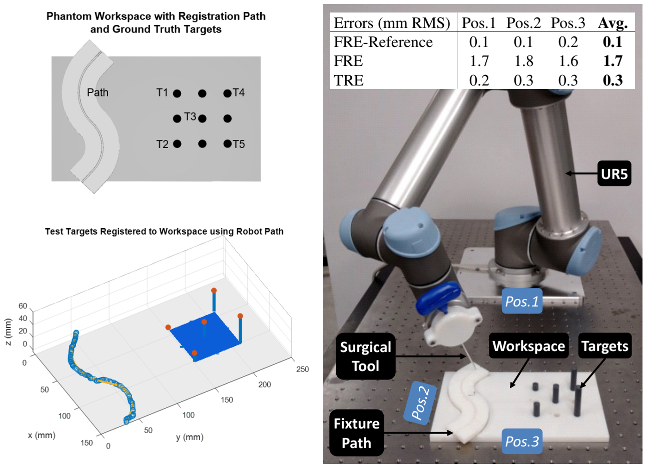
The straightforward principles of our approach make it broadly applicable to a variety of localization systems and robotics, while being conducive to product development and maintenance. The concepts can be engineered to specific clinical procedures, workflows, and constraints. In the example above, the fixture path is designed as a smooth channel that accepts passage of flexible, low profile devices such as catheters used in electrophysiology, transcatheter structural heart procedures, vascular interventions, and lung biopsies. For rigid devices such as robotic end effectors, the path may be a groove instead of a blind channel, and angular rather than smooth. Notably, the method can be used without any device alterations; it simplifies registration without disrupting other aspects of the workflow.

IV. EXPERIMENTS

A. *Registering a Robotic Device*

The principle is first demonstrated on registration of a robotic manipulator to a workspace, a scenario applicable to bedside laparoscopic assistants such as [40]. For quantitative evaluation, we construct a phantom workspace with five post targets spanning a 60-mm cube, as shown in Fig. 5 (*top-left*). This volume approximates surgical regions of interest such as the heart, prostate, and local anatomy peripheral to a lung tumor. The workspace coordinate system is defined per Fig. 5 (*bottom-left*). A 3D printout of the fixture path of Fig. 4 (*top*) is attached in a known configuration, 100 mm away from the posts. A Universal Robots UR5 arm is secured at an arbitrary position, and its end effector, a rigid needle used in orthopedic surgery, is backdriven through the fixture. Once completed, the path becomes known in both robot and workspace frames, thus registering them together.

Simulating versatility in making intraoperative setup adjustments, the registration is repeated with the robot base at three different locations with respect to the workspace, as labeled in Fig. 5 (*right*). In each trial, the robot visits each target and corresponding measurements are compared against the ground truth. The FRE using the path is found to be 1.7 mm, while the target registration error (TRE) is 0.3 mm. For reference, conventional landmark registration using these targets as fiducials leads to an FRE of 0.1 mm. The results are plotted together in Fig. 5 (*bottom-left*). Interestingly, the FRE in the proposed approach is higher than with the landmark method, yet the TRE remains nearly perfect. Beyond yielding accurate performance with a simplified workflow, this result demonstrates the robustness of path registration to errant or noisy data points—the continuum of samples along the path effectively serves as a series of fiducials.



Errors (mm RMS)	Pos.1	Pos.2	Pos.3	**Avg.**
FRE-Reference	0.1	0.1	0.2	**0.1**
FRE	1.7	1.8	1.6	**1.7**
TRE	0.2	0.3	0.3	**0.3**

Fig. 5. Registering a robotic device to a workspace. (*Top-left*) CAD model of a phantom workspace showing fixture path and ground truth targets. (*Right*) Experimental setup with a UR5 robot. Intraoperative adjustments to robot base are simulated by re-registering at the positions labeled in blue. Measured RMS errors are also tabulated. (*Bottom-left*) Plot of the registration result; robot path (hollow blue circles) overlays the model fixture (yellow line), while robot target positions (filled orange circles) overlay ground truth targets (blue posts). Workspace axes are also labeled.

B. Registering an EM Tracked Device

We next demonstrate the ability of the streamlined method to register a flexible EM tracked device such as a catheter, an instrument used in a variety of clinical interventions as previously noted. An EM field generator is stationed at an arbitrary position with respect to the workspace phantom described above, and the device is guided through the fixture. Once traversal is complete, the EM tracking system becomes registered to the workspace because the path is simultaneously known in both coordinate frames. Simulating both inter- and intraoperative adjustments of the EM tracking system, the procedure is repeated with the field generator at four different locations, as depicted in Fig. 6. The FRE using the path is found to be 1.8 mm, and the TRE ensuing from touching the device tip to the targets is 2.9 mm. For comparison, conventional landmark registration using the targets as fiducials yields an FRE of 2.0 mm.

The FRE is comparable between methods, but the TRE will likely be lower in the conventional case. Whereas fiducials and targets are typically conceived within each other's proximity, the path fiducial in the present setup is located remotely from the targets. Placing the target anatomy closer to the path may mitigate the influence of EM field distortions that otherwise plague larger workspaces. This provision may then be relaxed under navigation systems with less restrictive configurations, as evidenced by the robotic results above. Despite stringent EM working volumes, the proposed approach achieves sufficient accuracy for most cases (within a millimeter of conventional methods) while providing clinical users with benefits of simplicity and versatility.

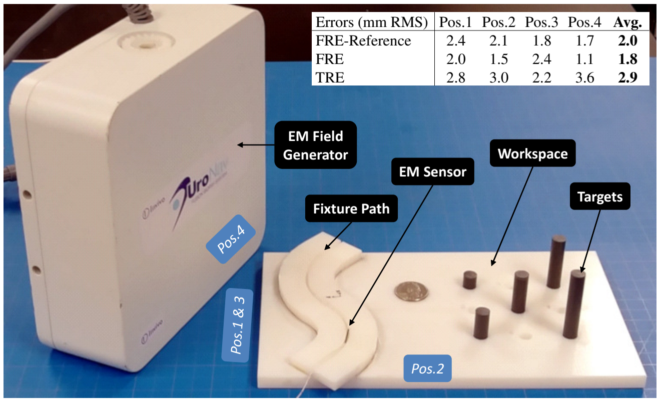
C. Discussion

A tantalizing exercise left for future work is the coordination of both the robot and catheter—that is, multiple tracked devices—into the same system. Not only would the benefit of an efficient workflow scale with complexity, the nature of the workflow may be redefined altogether. Device registration can be deferred to the moment of use, reducing the burden of registering beforehand. Registration of navigated devices to only each other can be obtained using a fixture that is decoupled from any particular workspace. Static preoperative arrangements give way to dynamic intraoperative adjustments: the repeatability of our approach is suggested by the standard deviations of 0.1 mm and 0.6 mm in the accuracy of the robotic and EM results respectively; direct validation of repeatability is slated for future work.

While the *S*-shaped path used in this study suffices for proof of feasibility, we note that the choice is not necessarily optimal. For example, the user may favor driving the robot through piecewise straight segments rather than curved ones, and in the case of catheters and guidewires, device stiffness may warrant retooling of curves. Meanwhile, intricate paths may be favored for computational robustness. Indeed, the concept of optimality may be intractable due to an expansive design space; the following section initiates a discussion on these considerations. Nevertheless, thematically consistent considerations including usability, implementation simplicity, and the psychophysics of perception, cognition, and judgment may serve as valuable guiding principles.

D. Design Considerations

Given the breadth of alternative fixture embodiments, a selection thereof is noted here for future reference. In terms of path complexity, usability may favor simpler paths that are shorter and straighter, but this may result in computational ambiguities that compromise the reliability of gesture detection (to be examined explicitly should any issues arise). So while complexity may be increased in response, residual inaccuracies can be resolved by tiering other capabilities instead. For example, intraoperative fluoroscopy or ultrasound can be used for image-based corrections; registration can thus remain simultaneously effective and user friendly even when individual methods are imperfect.



Errors (mm RMS)	Pos.1	Pos.2	Pos.3	Pos.4	**Avg.**
FRE-Reference	2.4	2.1	1.8	1.7	**2.0**
FRE	2.0	1.5	2.4	1.1	**1.8**
TRE	2.8	3.0	2.2	3.6	**2.9**

Fig. 6. Setup to register an EM tracked device (e.g., a catheter) with a field generator next to a workspace. Intraoperative field generator displacement is simulated by re-registering the device at multiple positions indicated in blue. Measured RMS errors are also tabulated.

Path traversal is presently described as a manual process, but other approaches may better fit different scenarios. For instance, the fixture may include active elements that engage and assist the device through the path. For flexible devices, a technique for pulling rather than pushing may be preferred, while a robot may guide itself under vision or force control when it is otherwise lost; this may hold particular promise for surgical microrobots [41]–[43]. The path itself may consist of discontinuous segments. For any given configuration, the computational problem can be constructed for efficiency and robustness, as mentioned in Sec. III-D.

Beyond the intrinsic design of the registration fixture itself, decisions on where and how it is mounted in the workspace can have profound effects on usability and functionality. For example, application particulars may determine the suitability of different mounting options, which may be the patient table, table rail, or patient anatomy. Specific requirements would further determine the feasibility of fixture sterilization, reuse, and integration as aftermarket addenda to existing systems. For facilities needing large variances in workspace coverage, multiple fixtures may be installed for improved accuracy and workflow.

V. CONCLUSIONS

Relating to a common experience, automotive GPS works without a pre-drive calibration—even though it would arguably be a worthwhile exchange for the benefits of vehicular navigation. Intuition suggests, however, that this hypothetical prerequisite would be distracting. Workflow disruption is inefficient: at best a nuisance, at worst a cognitive tax. “In the economy of action, effort is a cost” [44] leading to critical errors in driving [45], a fairly common task. The analogous phenomenon in surgical interventions—mentally demanding missions executed under pressure—is that motor skills and judgment are both compromised [44], [46].

In building the technicalities of registration into the system design upfront, we have developed a scheme that is streamlined for clinical users. We reason that user experience will grow in importance as discrete technologies are increasingly integrated to address clinical needs. This paper illustrates the approach with a robot and a flexible manual instrument, two instances of an overarching effort to make complex systems intuitive. Until devices can auto-register, we advocate for the elevation of users and workflows to beyond an afterthought, whether through standard platforms or protocols. The psychophysics of perception, cognition, and judgment can inform the design of navigation interfaces and workflows which may, as a side effect, alleviate subconscious reservations to innovation as well.

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