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A FRAMEWORK FOR OBJECTIVE EVALUATION OF HANDHELD ROBOTIC SURGICAL TOOLS AGAINST PATIENT NEEDS

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ABSTRACT

Surgeons are human: their best possible performance is limited by their neurophysiology. What if an inoperable patient's condition demands surgical treatment that exceeds such human performance limits? Can precision surgical robots help surgeons surpass such fundamental human neurophysiological limits? This article employs the Steering law to proposes a quantitative framework and benchmark tasks to evaluate the feasibility of a handheld surgical tool for meeting the quantified speed and accuracy requirements of a clinical need in non-contact interactions that exceed human limitations. Example use cases of such interactions in common surgical scenarios are presented. Preliminary results from a straight-line tracking task with and without computer assistance demonstrate the proposed framework in the context of falling short of a clinical speed/accuracy need. The framework is then used to articulate specifications for additional technology candidates to successfully exceed the speed and accuracy characteristics of the modality used.

1. INTRODUCTION

Historically, surgery has been a predominantly manual, subtractive manufacturing process: surgeons use handheld tools like scalpels in direct contact with tissue to remove volumes deemed undesirable. The ultimate accuracy and speeds achievable with such traditional handheld tools are limited by the neurophysiology of the humans that wield them. For example, the time delay of neural control of muscles alone is known to introduce a fundamental cap on the achievable speed-accuracy capabilities of human hand motion in the context of Fitts law [1].

Consider so-called "no option" patients whose conditions are currently deemed surgically inoperable. What if a future surgeon looks to technologies for innovating treatments via procedures that demand speeds and accuracies that exceed human neurophysiology? Even today, gaming computer mice (>5000 dpi, <5 micron resolution) [2], tremor-cancelling surgical robots [3], and driver assist cars outperform physical human accuracy beyond its neurophysiological limitations. But considering accuracy alone is not enough. Doubling spatial or temporal resolution of sensors (or actuators) at the tip does not imply doubling of overall accuracy and speed of handheld tool use by a human. For example, use of a computer mouse or stylus exceeds freehand tool capabilities in accuracy by 1.8-57.4% [2]. But boosting mouse resolution past roughly 1000dpi provides no measurable accuracy improvement [2], yet marketing for 5,000-20,000 dpi is typical. This misleads consumers into unnecessary technology; do surgical robots threaten similar overpromise?

Suppose a future surgeon needs to bioprint directly inside a living patient to regenerate vessel walls or lase away endometriotic bowel lesions at a 50μm accuracy for a given volume of tissue in under 1 hour. Is there a way to quantitatively measure whether a current or future handheld robot can practically boost their performance capability to such an extent? Determining the theoretical bounds on performance of humans using handheld computer-assisted tools based on typical human hand motions and technology-agnostic characteristics of spatial resolution, combined speed, sampling rate, and actuation response time would help answer these questions.

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1.1 Objective and Scope

The objective of this paper is to 1) introduce a quantitative framework founded on the Steerling law to evaluate whether handheld computer-assisted surgical tools will or will not meet a given clinical need with quantitative accuracy and speed requirements that may exceed human physiological capabilities and 2) provide example use cases of this framework applied to possible clinical needs and candidate technologies that purport to meet them.

We constrain our analysis to handheld tools with instrumented tips that regulate non-contact interactions with target tissue. This can be either additive modes (as in drop-on-demand inkjet bioprinting [4–6]) or subtractive modes (as in pulsed laser machining like excimer laser cold photoablation). We further constrain the work to a simple prototoask of effecting a continuous, geometrically-constrained line on a planar surface as a basic subunit from which the Steerling law can extend to more complex geometries or tasks.

1.2 Hypothetical Motivating Clinical Use Cases

The emerging robotic technology of intra-operative bioprinting provides an extreme example. Preliminary work has demonstrated 3D printing of live tissue onto moving human anatomy at a macro-level [4, 5] and even considered in-situ and in-vivo bioprinting [7]. If such technologies are scaled to resolutions at the microscopic level (e.g. $100\mu m$) it would be possible to print vessel endothelial tissue to repair ruptured blood vessels, construct micro-vasculature as an alternative for deep burn grafting, or reconstruct features previously considered collateral damage. However, the resulting procedure times would likely be prohibitively long unless *both* accuracy and speed are scaled.

Subtractive techniques are historically more mature in surgery than additive ones like bioprinting and provide established examples of surgical intervention that could benefit from such precision technology. For example, consider subtractive laser surgery, where a laser scalpel is used to precisely remove endometriotic tissue. Over 190 million women of ages 15 to 44 globally are diagnosed with endometriosis [8], a disease in which endometrial tissue, the tissue lining the inside of the uterus, grows outside uterine cavity and implants into other organs such as the peritoneum, ovaries, bladder, intestine, and even lungs, resulting in chronic debilitating pelvic pain [9]. For intestinal endometriosis, laparoscopic procedures are considered a gold standard. Using a laparoscopic tool, manual or robotic, the surgeon examines the abdomen for the presence of endometrial tissue, which varies in appearance from light discoloration to chocolate cysts or red nodules [10]. Any time a tissue is identified, the surgeon uses either a bipolar cautery, or CO_2 laser scalpel to make a shallow circular incision around the tissue, usually $2-6$ cm in diameter, and a thin layer ($3-5$ mm deep) of tissue including the nodule or cyst is excised from the organ [10]. If the incision becomes too deep, as is the case when the nodule is >5mm in stage 3-4 deep infiltrating endometriosis, it can perforate the bowel and requires suturing. An extreme example would require a surgeon to laparoscopically 'run the bowel' (carefully examine the intestine by progressing grasper to grasper) in search of lesions and progressively ablate them along the way which is time consuming for manual diagnosis, likely to miss early (e.g. submillimeter) lesions, and ill-advised on the small intestine wall with its average thickness of 1.8mm [11]. However, if computer-assisted precision is made available at the surgical tool tip, while the surgeon retains high-level decision making and typical hand speeds, such cases could be addressed as early as diagnosis with same-day recovery because of shorter anesthesia time, smaller incisions, and minimal damage to healthy tissue. Early treatment would also avoid the disease progressing to a stage that requires aggressive intervention and resection or removal of diseased organs [8].

Other surgical applications that could benefit from subtractive surgery with robotic precision and speed are: damage-free excision of papillomas in the throat, suture-less anastomosis of microvessels in maxillofacial procedures, scar-revison, and acne reversal. Many of these tasks often require a level of precision not achievable under human neurophysiological limits, but can be achieved readily with precision technology. Whether the resulting handheld computer-amplified precision results in accuracy and speeds that meet a clinical need remains to be determined. In that regard, the major emphasis of this work is to apply the well-established Steering law to induce a quantitative framework for evaluating existing and future technologies against surgical need.

2. MATERIALS AND METHODS

For spatial tasks, precision and speed are inversely related to one another [12, 13]. Figure 1 illustrates this phenomena noting some surgical targets and human-computer interaction devices. Tasks that require a higher level of precision such as eye surgery ($0.001-1$mm) are performed at a much slower speed (30μm/sec) than tasks that do not require it. Regardless of procedure, the typical speeds of human hands (and robots) in surgery fall well below neurphysiolgical maxima, such as professional baseball pitcher's peak hand speed. Similarly, tasks involving longer travel i.e. greater target length, require a longer movement time but not necessarily slower speed. The Accot-Zhai Steering law describes how humans typically slow their speed (reduce movement time T for a given target length L) when the allowable target width W decreases along an arbitrary hand motion trajectory. This can be projected onto a simple straight-line-in-narrow-tunnel task as equation 1 [13]:

$$T = a + b\frac{L}{W} \tag{1}$$

Here a is the x-axis intercept that could be interpreted as the fastest achievable time L/v_{max} for moving across distance L with no width constraints at maximum hand speed v_{max}, for example, typical handwriting speed. This can be thought of as a user-specific constant signifying their most comfortable speed of free-hand motion. Whereas b, the slope, indexes how quickly a user moves within a narrow, constrained tunnel of allowable width W and length L, adding an overall time penalty of $b\frac{L}{W}$. This law states that with human neurophysiology, a tenfold increase in accuracy ($W_2 = W_1/10$) will result in a tenfold decrease in speed ($T_2 = 10T_1$) while keeping L and b constant. To provide clinical value, a computer-assisted hand tool must break past this limit, either by boosting accuracy at the same speed (this alter effective b by a factor of 10) or at a proportionally faster speed (e.g. alter effective b by a factor of 100). An ideal handheld robotic device can fulfill both high speed and high precision tasks and would fit into the lower left corner of the plot in Figure 1.

2.1 Benchmark Tasks for Evaluating Handheld Tools

The Accot-Zhai Steering law [13] is benchmark for human performance alone. Applying it as a benchmark for handheld robotics expands a well-established, non-controversial quantitative framework to compare the effectiveness of current and future technologies. This suggests a simple, intuitive task to benchmark proposed computer-assisted handheld tools: drawing a "continuous, perfectly straight line" with a handheld tool. Users attempt to draw a perfectly straight line within a tunnel of two parallel lines (length $L = 100$ mm, $W = 4$ mm) using the proposed tool both with and without computer assistance. This is in accordance with the baseline freehand tool-use accuracy of 4 mm in humans [2]. The procedure is repeated for a tenfold decrease in width (e.g. $L = 10cm, W = 400\mu m$). Further instances of decreased width may occur until measurement resolution is exceeded. In each case the extents of the drawn line provide the effective width W and duration yields movement time T. Assuming a constant user-specific a, the resulting change in b between assisted and unassisted cases yields the measure of how far computer assistance boosts dexterity past the limits of human neurophysiology: no change in b indicates no improvement over human neurophysiology, a decrease in b measures the extent to which dexterity is improved beyond human neurophysilogical limits (e.g. $\hat{b} = b/2$ implies that accuracy is doubled for the same speed and $\hat{b} = b/4$ implies that *both* accuracy and speed are doubled).

2.2 Preliminary Experiments

A preliminary handheld prototype is devised to demonstrate the concept of benchmarking proposed improvement of dexterity with handheld computer-assisted tools. Materials with form factors that are, in principle, compatible with typical laparoscopic scenarios and tools and previously demonstrated to successfully

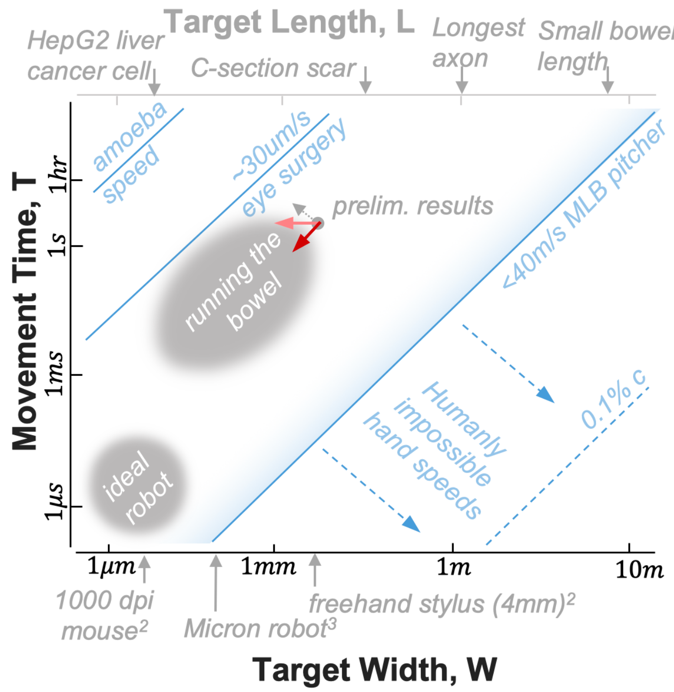

FIGURE 1. ILLUSTRATION OF PROPOSED FRAMEWORK TO SPECIFY WHETHER PROPOSED HANDHELD ROBOTIC TECHNOLOGIES MEET QUANTIFIED CLINICAL NEEDS. SPATIAL PRECISION AGAINST MOVEMENT TIME WITH REPRESENTATIVE HAND SPEEDS OVERLAID. THE APPROXIMATE TARGET AREA FOR A RUNNING THE BOWEL PROCEDURE IS SHOWN (A 20 MINUTES AVERAGE PROCEDURE TIME IS ASSUMED). IDEAL HANDHELD ROBOTIC DEVICES HAVE HIGH PRECISION AND FAST MOVEMENT TIMES, ALBEIT IN A MODEST REACHABLE WORKSPACE. PRELIMINARY RESULTS SHOW A DOUBLING IN ACCURACY (TARGET WIDTH BOOST FROM 2.37MM TO 1.23MM) BUT AT THE EXPENSE OF MOVEMENT TIME (STEERING LAW $\hat{B} = B$). A TRUE DOUBLING IN HANDHELD TOOL DEXTERITY MUST PROVIDE A DOUBLING IN ACCURACY EITHER AT THE SAME SPEED (E.G. LIGHT RED ARROW $\hat{B} = B/2$) OR AT A DOUBLED SPEED (DARK RED ARROW $\hat{B} = B/4$).

bioprint viable cells provide a surrogate additive manufacturing scenario. An inexpensive 4mm USB camera (4mm Supereyes Otoscope 1 Megapixel) is affixed to an HP51604A inkjet printhead, driven by the InkShield [14], an open-source Arduino compatible breakout board. Figure 2A shows a zoomed-in view of the HP printhead with 12 its nozzles, previously shown to successfully bioprint cells [6,14]. Each nozzle is approximately 80μm in diameter. The inkjet head is programmed to constantly fire only a single nozzle. In unnassisted mode, this nozzle is always on. In assisted mode, it is fired only when it is within the target width.

The target is recognized via computer vision using the OpenCV Python library. The total closed loop latency in the system from recognizing the target to firing or stopping the nozzle is observed to be approximately $30-100$ms. The latency in the inkjet head alone without a computer vision loop is about 1ms.

The users (authors) attempted to draw 'continuous, perfectly straight lines' on backlit white paper with the handheld tool and could freely look at a live video feed of the close-up ink deposition on an adjacent computer screen or directly at the tool tip/paper target site. Prints were then optically scanned at 1200 dpi and post-processed in MATLAB for accuracy.

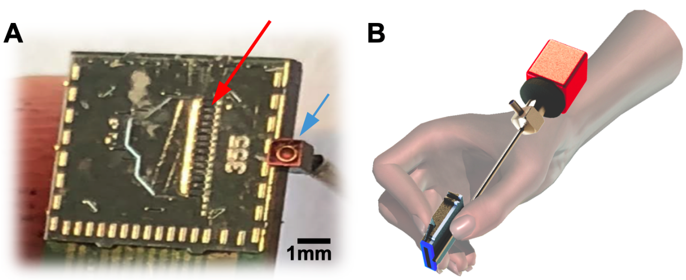

FIGURE 2. **A**. CLOSE-UP OF 12-NOZZLE INKJET REMOVED THE HP HP51604A PRINTHEAD THAT WAS USED IN PRELIMINARY EXPERIMENTS; RED ARROW: SINGLE 80μM NOZZLE; BLUE ARROW: MINNIECAM XS OR SIMILAR OV6948-BASED DISPOSABLE ENDOSCOPE CAM THAT MAY BE CONSIDERED FOR FUTURE WORK. **B**. PROPOSED INKJET WAND USING A XAAR128 PRINTHEAD (BLUE) AND INIVATION DVXPLORER MINI EVENT CAMERA (RED) ATTACHED TO A 2.7MM DIAMETER OTO/ENDOSCOPE (TUBING AND WIRES NOT SHOWN) TO OVERCOME LIMITS DEMONSTRATED IN PRELIMINARY RESULTS.

3. RESULTS AND DISCUSSION

Figure 4 shows a comparison of the final accuracy, measured as extent-derived effective width, achieved using the human hand unassisted in free space against the human hand actively assisted by the injket and USB otoscope control loop. These results show that the accuracy achieved with the active-assist is twice that of the freehand spatial accuracy of the human hand and and surpasses typical 4mm unassisted freehand accuracy [2].

However, this accuracy is achieved at the expense of line discontinuities as indicated by the blue arrows in Figure 4. While this demonstrates the ability of the tool to prevent mistakes in real-time (i.e., from motions that exceed the effective width due to essential hand tremor or unpredictable disturbances) it lacks the continuity of the unassisted line. This could be improved by enabling the same algorithm on all 12 nozzles, and not just a

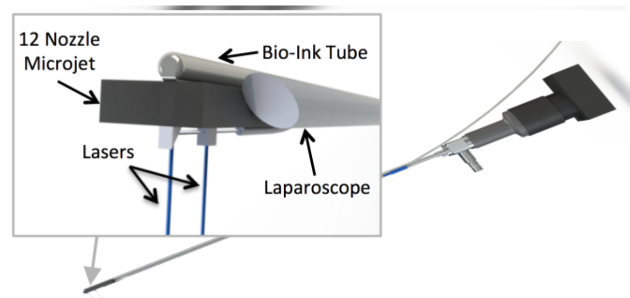

FIGURE 3. CONCEPTUAL DEMONSTRATION REPEATED FROM [15] SHOWING HOW EXISTING 12-NOZZLE INKJET HEAD FROM PRELIMINARY RESULTS (FIG 2) CAN COUPLE WITH LASERS AND BIO-INK DELIVER AT THE TIP OF A TYPICAL 90° LAPAROSCOPE WHICH MAY ACCEPT A VARIETY OF HIGH SPEED CAMERA TYPES AT ITS EYEPIECE. THE RESULTING FORM FACTOR IS CONCEIVABLE FOR KEYHOLE SURGERY.

single one, increasing the sampling rate of the computer vision loop, and decreasing system latency.

More importantly, this twofold increase in effective accuracy (decrease in W) is achieved in more than double the time of the unassisted case. That is, the benchmark value b stayed constant (or increased). Thus, while the system appears to double overall accuracy, it in fact does not boost overall human performance beyond the limit dictated by the Steering law. While enabling all 12 nozzles (or possibly hundreds of others on other inkjet heads) would increase the effective width (e.g. by roughly a factor of 12) to suggest an improvement in effective $\hat{b} = 12b$, the increase in speed (Time T) is fundamentally capped by the slow latency of the computer vision system and the likelihood that sensing accuracy will only degrade with higher speeds due to motion blur.

3.1 Implications of Framework for Existing or Future Technologies

Small endoscopes like the OV6948-based disposable endoscope cam (Fig. 2A) promise vision sensing collocated with the end-effector (e.g. inkjet or laser) but still suffer from limited spatial resolution. Instead, rigid rod 'Hopkins' lenses which are ubiquitous in existing clinical otoscopes, orthoscopes, and endoscopes provide unrivaled resolution and magnification capability at the tool tip and are amenable to other camera types. While such imaging improvements promise improved spatial sensor resolution, the latency of image acquisition will still fundamentally bound the theoretical boost in Steering law $\hat{b}$ parameter. For example, even with unlimited camera spatial resolution, the target anatomy may exhibit an unpredictable motion occurring during the sensing latency time which will bound the effective spatial accuracy of any time-sampled sensing system. This issue is further confounded by the freehand use case. A different type of imaging technology would be required to overcome this fundamental limit. On alternative may be neuromorphic event cameras (Fig. 2B) which provide dramatic improvements in latency (time delay) without motion blur and much smaller data rates for processing. This resulting boost in accuracy (width) would *not* come at the expense of time (speed) and no consistent maximum speed would emerge as with global shutter cameras due to motion blur.

The inexpensive inkjet used in the preliminary work has relatively poor resolution. Modern inkjets boast orders of magnitude higher nozzle count, tighter nozzle pitch (spacing), and smaller nozzle diameters (drop sizes) for better control. Future tools may exploit these technologies up the the limit of minimum nozzle size required for bioprinting (typically $> 20\mu m$ for average human cells. We expect that Steering law speed $W/b = L/T$ will follow a W corresponding to the width of the inkjet array and *not* target line width. Similar considerations arise for subtractive techniques like laser scalpels: either a fiber array, galvanometer scanner, or scanning fiber actuator would improve the precision and latency of the system.

A combination of such techniques, coupled with an inertial motion unit for accelerometer and gyro data at the tip would help achieve Steering Law $\hat{b}$ values that would exceed limitations of human neurophysiology.

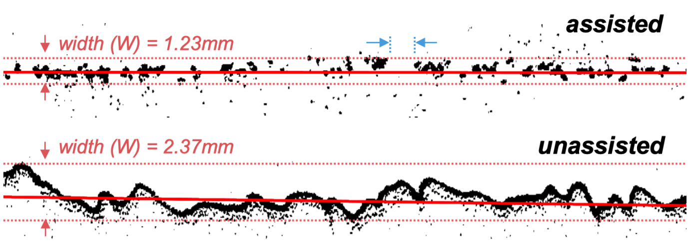

FIGURE 4. PRELIMINARY RESULTS OF BENCHMARK TASKS: FREEHAND, CONTINUOUS STRAIGHT LINES DRAWN BY EARLY HANDHELD PROTOTYPE FIRING A SINGLE INKJET NOZZLE VIA NAIVE COMPUTER VISION (≈30-100MS RATE). RED DASHED LINES SHOW ERROR EXTENTS. COMPUTER ASSISTANCE BOOSTED SPATIAL ACCURACY (FOR A SINGLE NOZZLE) BUT AT THE COST OF LINE CONTINUITY (BLUE ARROWS) REQUIRING ADDITIONAL SUBSEQUENT PASSES AND HENCE MORE TIME TO FIX. ALTERNATELY, FIRING THE ADJACENT NOZZLE COULD KEEP THE LINE CONTINUOUS AS IN THE UNASSISTED CASE WITH 1MS REPEAT RATE AND SIMILAR SPEED, THUS YIELDING A TRUE INCREASE IN STEERLING LAW $\hat{B}$.

3.2 Future Work

Only the simplest task primitive of 'continuous, straight line' following was considered to illustrate the proposed framework in this paper. Future work should spell out how this is typically extended to more complex tasks such as completely covering an arbitrary target lesion surface with therapeutic 'hits' of known spot size, as is widely spelled out in Steering law literature for computer user interface literature. Furthermore, future work should provide a more thorough, representative treatment of quantified clinical needs. Ideally, this would be a public repository to serve as an atlas of quantified clinical needs. This would yield consistent, citable target performance specifications (and means of confirming them) that developers of handheld computer-assisted tools can leverage.

4. CONCLUSION

In this paper, we introduced a framework to quantify clinical needs with quantitative speed and accuracy requirements through the lens of the Steering law along with a simple benchmark straight-line task derived from the it. The resulting $\hat{b}$ value provides a means to measure whether an existing or future handheld computer-assisted surgical tool will or will not exceed human physiological capabilities, and thereby better inform surgical robotics research and use. The use case of handheld computer-assisted tools capable of performing additive and subtractive manufacturing without contact through inkjet printing and laser scalpels served to illustrate the proposed framework.

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