Effect of reduced stereoscopic camera separation on ring placement with a surgical telerobot

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ABSTRACT

A custom, stereoscopic video camera was built to study the impact of decreased camera separation on a stereoscopically viewed, visual-manual task resembling some aspects of surgery. The camera's field of view was matched to that of a stereoscopic laparoscope by adjusting focal length and viewing distance so that the viewer could see equivalent image content at a plane orthogonal to their view. This plane contained the point at which the left and right viewing axes converged. This geometry only exactly matches the images from both the laparoscope and the stereo-camera at this point. This condition was considered a useful approximation for a match between the two image sources. Twelve naïve subjects and one of the experimenters were first trained in a ring placement task using the stereo-laparoscope and subsequently switched to the stereo-camera. It was used with differing camera separations ranging from 100% of the laparoscope's separation to a biocular view corresponding to no separation. The results suggest that camera separation may be reduced 20-35% without appreciably degrading user performance. Even a 50% reduction in separation shows stereoscopically supported performance much better than the biocular condition. The results suggest that existing laparoscopes which use 5 mm camera separation may well be significantly miniaturized without causing substantial performance degradation.

Keywords: stereoscopic display, laparoscopic surgery, inter-camera distance, human factors

1. INTRODUCTION

Stereoscopic visual information is a well known source of depth information and has long been established as a basis for improved telemanipulation, particularly in cases in which alternative depth cues are missing[1]. There has, however, been controversy regarding benefits of stereo for laparoscopic surgery. Some studies have reported essentially no clinical benefit from the addition of stereoscopic information during minimally invasive surgery[2] whereas others based on the use of alternative stereoviewing technology claim that clinical benefits may yet be demonstrated[3].

Some of the costs related to dual channel stereo-laparoscope are attributed to the increased size of the stereo-laparoscope which to a first approximation could be twice the diameter of single channel scope. One obvious technique to address this problem is to further miniaturize the entire system. Miniaturization raises many design challenges. A key one is that making the laparoscope smaller could reduce the separation of the two visual channels and thereby reduce the effectiveness of the stereoscopic information through reduced binocular disparity.

Reduced camera separation is well known to degrade the performance of users of stereoscopic systems. Geometrically, one could expect that the effect of reduced camera separation might be a linear reduction in performance. However, because the human visual system is much more than a simple camera with geometrically computable effects[4], even simple visual depth judgments made via stereo-cameras degrade nonlinearly with reduced intercamera separation[5]. The specific nonlinearities arise not only from processing within the visual system itself but also from aspects of the response elicited from experimental subjects used for specific studies. Purely perceptual judgments, such as the report of a visual change, which are used in signal detection experiments might be the most likely to be free from response nonlinearities. However, such judgments are often distantly removed from the actual behavior that stereoscopic displays are intended to support.

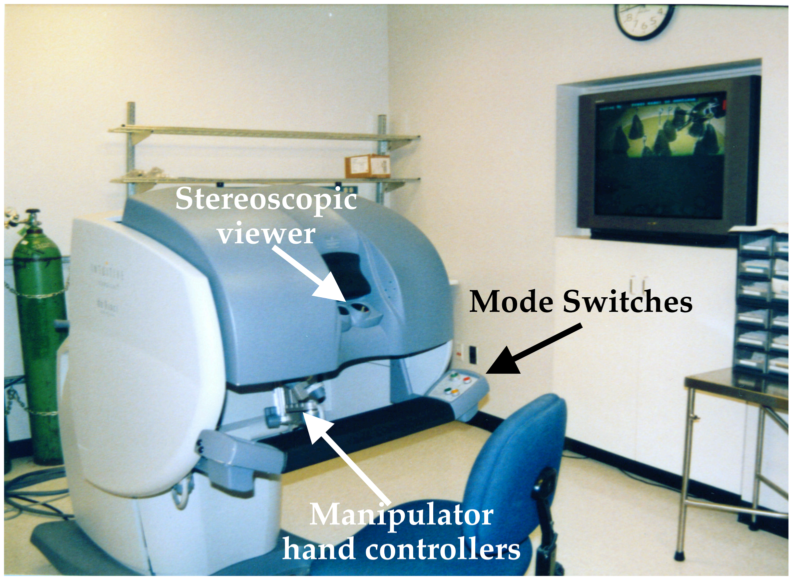

Figure 1: *Da Vinci* Master

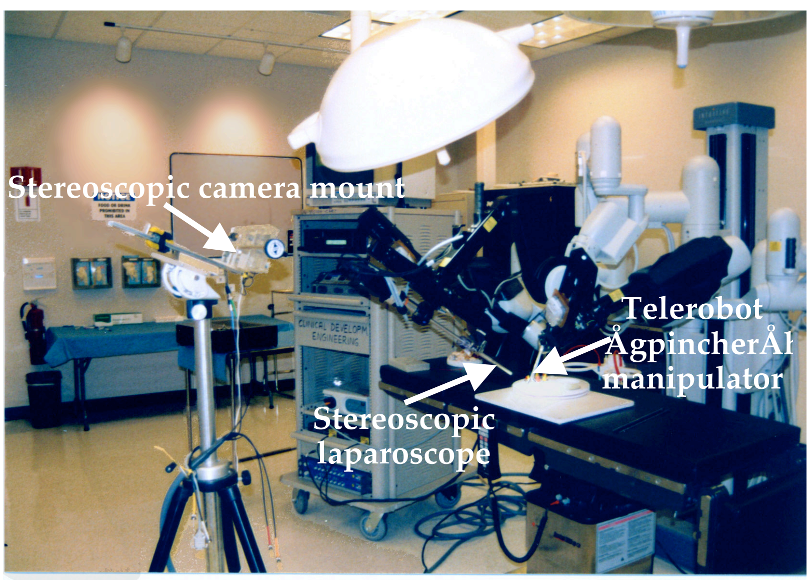

Figure 2: *Da Vinci* Slave system and stereo-camera

Consequently, the assessment of the impact of a reduction of inter-camera separation needs to be studied in the context of a complex, closed-loop task closely related to intended user performance[2,3] and not a simple visual alignment task as has been used previously, for example, by Rosenberg

(1993). In order to determine the effect of reduced camera separation with such a task, an experiment was designed to use the *da Vinci* surgical telerobot system (Figures 1, 2)[6,7] and a miniaturized stereoscopic camera created at NASA Ames (Figure 2) to study the effects of reduced separation. The selected task was the placement and removal of a set of eight small rubber rings on eight irregularly placed wires mounted on small posts.

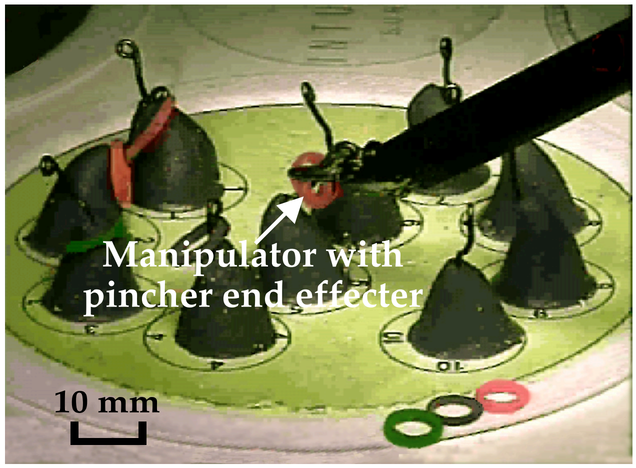

Figure 3: *Da Vinci* manipulator placing a rubber ring on a wire mounted on the task board.

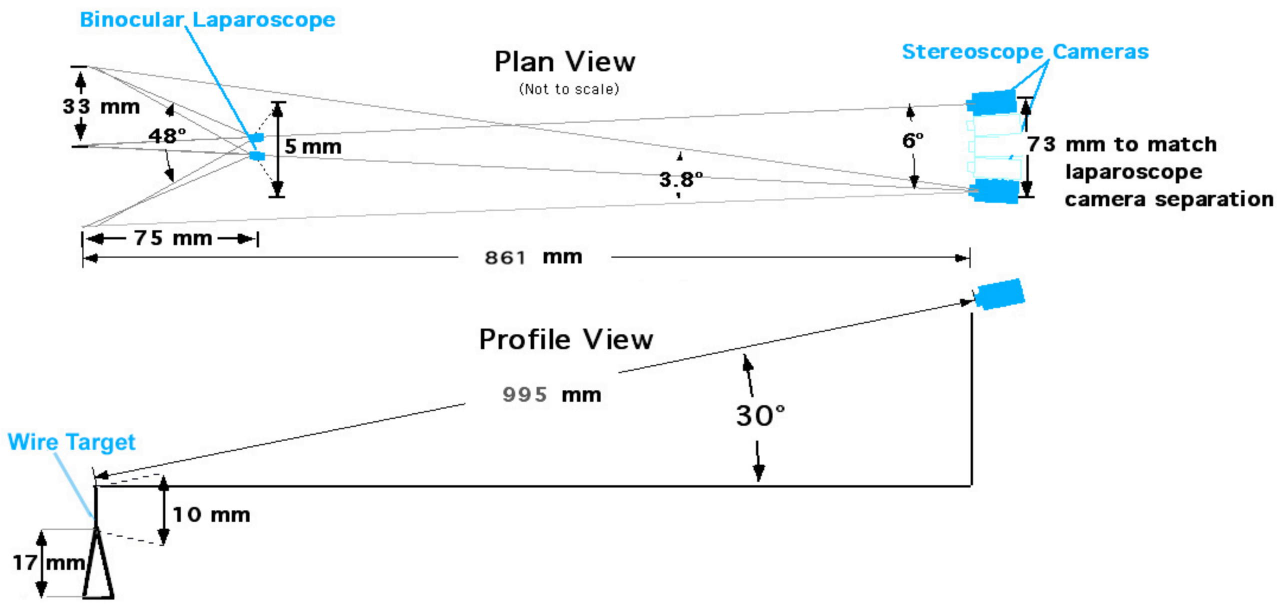

Figure 4: Viewing geometry for stereo-laparoscope and matched stereoscopic cameras

2. METHODS

2.1 Apparatus

A *daVinci* telesurgery system provided miniaturized, seven degree of freedom surgical manipulators which can be precisely controlled in three dimensional space, by a subject operating it through a view much like a stereoscopic dissection microscope. This system is a high-fidelity telerobotic surgery system (See for example United States Patent 6,720,988) in widespread international use. Though the system provides bilateralteral manipulators, subjects mainly used the manipulator driven by their dominant hand. The experiment was set up such that the subject's view into the *da Vinci* Master Unit visual display (Figure 3) corresponded with either the *da Vinci* laparoscope (for the 'learning' phase), or the Ames stereoscopic camera (for the 'testing' phase). The alternative viewing geometries are illustrated in Figure 4.

2.2 Subjects

Twelve subjects either from NASA Ames personnel or Intuitive Surgical's work force participated in the experiment. They had a variety of different backgrounds varying from development engineers to psychology graduate students. Subjects were excluded from the study if they were considered stereo-blind either through subjective reporting of problems with depth perception, or through objective testing with random dot stereograms. Ten male and 2 female subjects ranged between 25–51 years. Their interpupilary distance varied from 58 to 70 mm. They were assigned to one of three groups of four: *Unfamiliar, Familiar*, and *Experienced*. *Unfamiliar* subjects had had no previous contact with the Master *da Vinci* control station. *Familiar* subjects had had some episodic contact with it. *Experienced* subjects used it on an almost daily basis. Data from one of the authors (JMF) was also included in the *Unfamiliar* group bringing the total number of participants to 13.

2.3 Procedure

The task itself consisted of a conventional 'pick and place' task. The task-board, as viewed by the subject through the teleport at the Master control station, consisted of a set of 10 cones and the subject was instructed to place 8 rings, of differing size, in numerical order on the first 8 and then remove them in reverse order and place them outside the perimeter of the task-board to complete the task. The total time taken to complete the task was recorded. If a subject failed to complete the test for whatever reason, then the task was repeated and timed again from the start.

Subjects were informed that we were investigating new design parameters for the *da Vinci* system, shown how to perform the task and allowed to familiarize themselves with it by using the full *da Vinci* system, i.e. the Master control station set up with a view through the stereoscopic laparoscope. Then they began timed repetitions of the task until a point was reached at which the time taken to complete the task approached an asymptote, defined as the 3 consecutive completion times within 10% of each other. The mean of these values provided an individualized reference time for each subject that could be divided into their subsequent time measures. Thus for each subject a normalized time value of 1.0 thus means that there has been no change relative to this baseline, other values indicate proportional increases or decreases. Normalized data were sought since the focus of the experiment was the relative degradation of performance that would be caused by reduction of the camera separation as might accompany a further miniaturization of the stereo-laparoscope.

At point the subject was considered trained, the image source was switched to the Ames stereo-camera set to a separation matching that of the stereo-laparoscope. Given the relative magnifications of the two alternative camera systems, it was determined that a stereo-camera separation of

73 mm matched that of the stereo-laparoscope when the camera slant viewing distance was 995 mm. We are aware that this matching is only complete for the immediate vicinity of the point of camera convergence as described in the caption to Figure 5. The stereo-camera viewing geometry only matches that of the stereo-laparoscope to a first approximation. However, as noted below in the Results, the matching has some face validity since the mean completion time for the task for the laparoscope and the matching 73 mm separated stereo-cameras were quite similar: Mean ±Standard error; Laparoscope: 1.561 ±0.117 min.; Stereo-camera w/ 73mm baseline; 1.556 ±0.084 min.

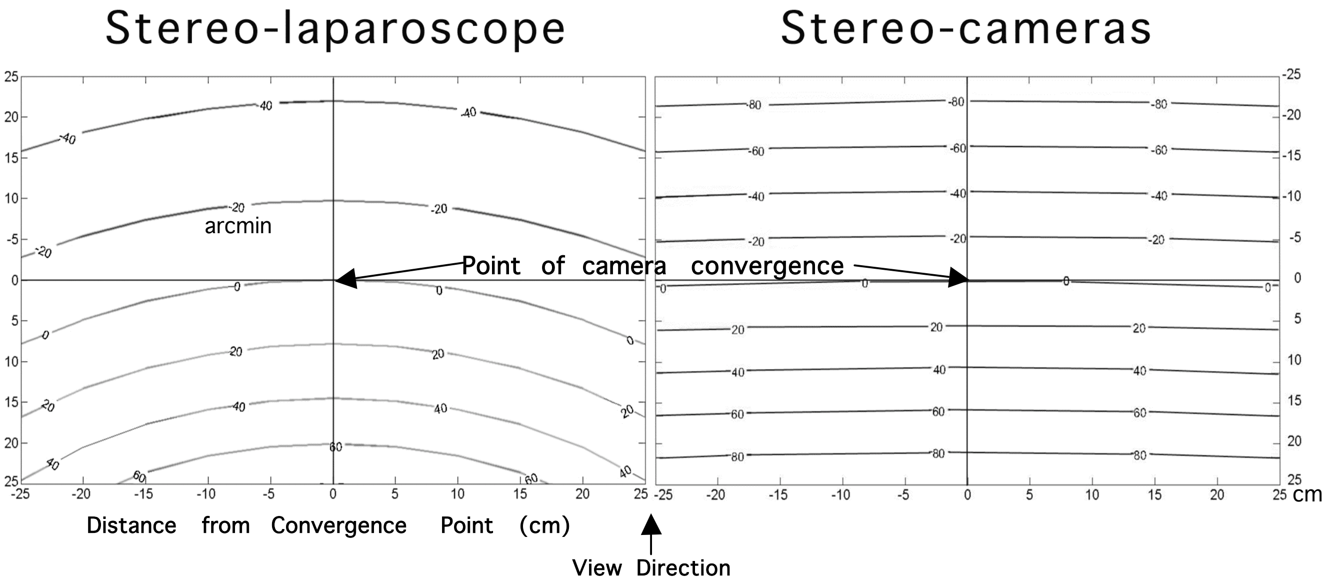

Figure 5: A comparison of the disparity fields for "matched" viewing conditions between the stereo-laparoscope and the stereoscopic camera. These plots show the variation in binocular disparity as presented in the stereoscopic displays for a square plane of space centered at the point of camera convergence. For these data the laparoscope was 87 mm from the point of camera convergence along the line of sight and the corresponding stereo-camera distance was 995 mm. The focal length of the camera was changed to match the lateral extent of the scene in both views. Though this subjectively makes the two views similar and testing showed that ring placement performance was not significantly different in the two conditions, the isodisparity contours above show that the two conditions are markedly different. The curvature and fore-aft asymmetry in the disparity field for the laparoscope are due to the proportionately greater changes in disparity caused by changes in target position relative to a nearby pair of eye-points. Though the change in magnification used for the stereo-camera brings the range of disparities into the same general range as that of the laparoscope, it does not completely reproduce its stereoscopic stimulus.

The time taken to complete the task was measured for a range of inter-camera separations which were assigned in a randomized fashion within each block replication. Each subject completed 3 replications. Each replication consisted of a sequence of the completed tasks beginning with camera separation corresponding to the stereo-laparoscope, i. e. 73 mm, followed by a random sequence of four different camera separations expressed as a percentage of the normal laparoscope separation, i.e. 0%, 22%, 51%, 75%.

3. RESULTS

All results reported below are based on analysis of normalized completion time because this variable reflects most directly the relative impact of changes in camera separation on performance, but alternative analyses based on raw completion times also showed statistically identical results.

A preliminary examination demonstrated that the data were normally distributed with equal variances and that parametric statistical analysis was appropriate. For example, the aggregate data when expressed as a cumulative distribution was almost perfectly fit by cumulative normal distribution with mean of 1.69 min and standard deviation of 0.37 min (r^2 =0.999).

An initial ANOVA was conducted in which Subjects were nested within Experience-Levels and crossed with Inter-Camera-Separation and Replication-Block. This analysis showed a significant effect of Replication-Block ($F(2,20)=6.17$, $p < 0.001$) illustrated in Figure 6. which shows that subjects had not reached asymptotic performance until the second replication. Consequently, the ANOVA was recalculated excluding the first block of data to avoid training effects that could cloud the experiment's focus on the impact of reduced camera separation on practiced tasks. When analyzed in this manner, the only statistically significant effect detected in the data was the main effect of Inter-Camera_Separation illustrated in Figure 7 ($F(4,40)=28.6$, $p < 0.001$). Notably, significant main effects and interactions involving Experience Level disappeared once subjects had at least one block of experience with reduced camera separation. Noteworthy also is the near equivalence of performance with the stereo-laparoscope and that of the matched inter-camera separation, i.e., 100%.

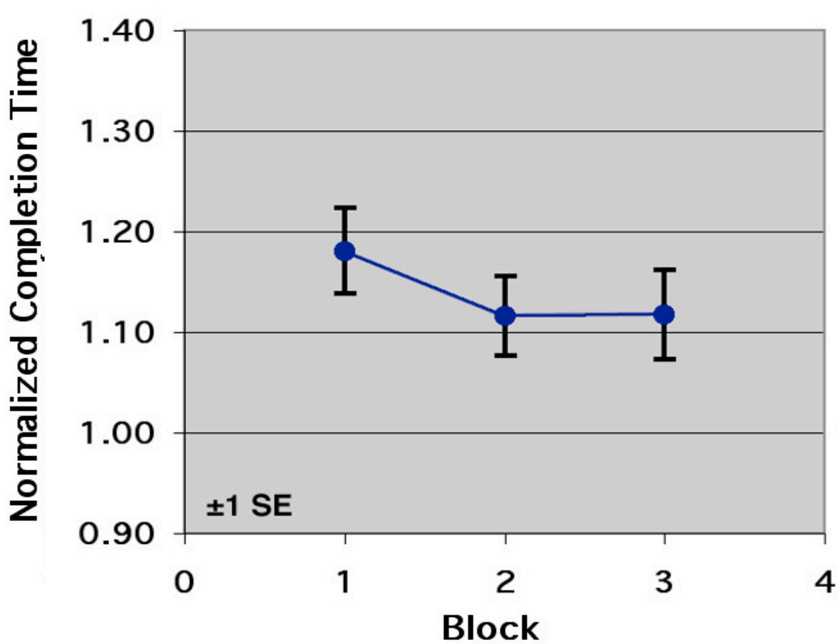

Figure 6: Effect of Replication-Block on task completion.

4. DISCUSSION

That reduction of inter-camera distance degrades user performance on a task for which binocular disparity can provide helpful relative distance information is not surprising. The interest is rather in the specific shape of the function describing the degradation. Purely stereoscopic depth judgment tasks which are designed to depend entirely on disparity information can show a steep decline in performance when the inter-camera distance crosses a threshold below which there is insufficient stereo information to accomplish the task[5]. Our results show a similar kind of plateau when the separation changes from 100% to 75%, a plateau most likely caused by the subjects using alternative depth cues such as interposition, shadowing and visual feedback of contact with the visible manipulator.

These alternative depth cues are known to be useful, especially in situations in which a standard unchanging view is used[8]. However, they are of relatively limited use and can only partially substitute for more direct depth cues such as stereopsis and motion parallax. Consequently, as camera separation is further reduced, performance finally does deteriorate. Significantly, we have evidence that even with a reduction of about 50% of the normal inter-camera separation, there is clear evidence for the presence of useful disparity information when assessed using a complex placement task that exercises some manipulation skills useful during laparoscopic procedures.

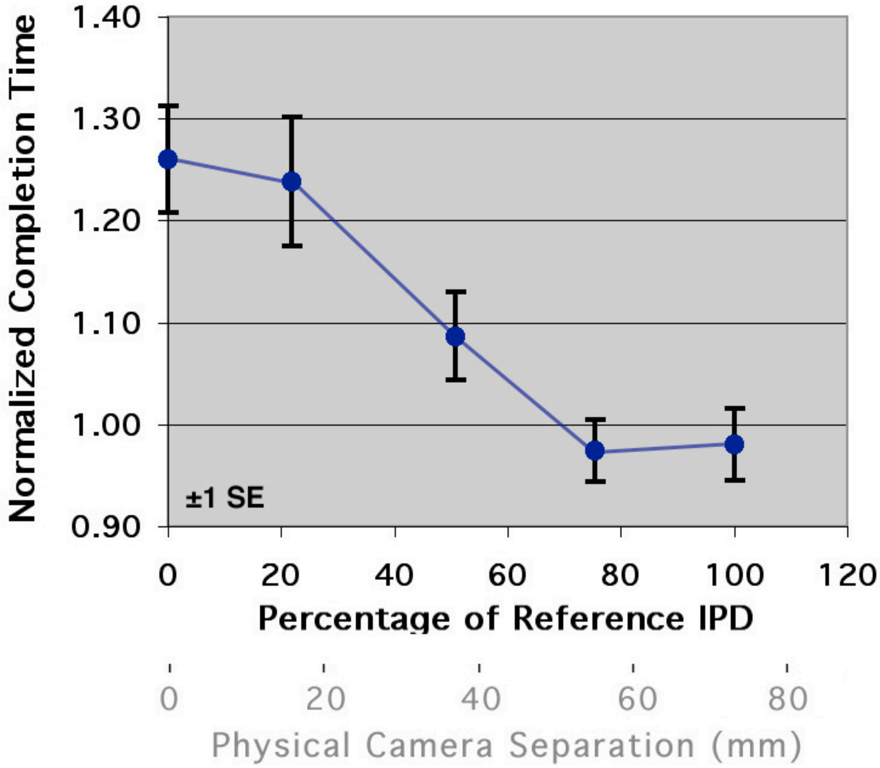

Figure 7: Effect of reduced camera separation on task completion.

We additionally see another approximate performance plateau when the inter-camera separation approaches zero. This behavior is likely related to the specific movement task but we do not have enough behavioral information, such as movement trajectories, to speculate more specifically about its cause.

The present results thus suggest that further miniaturization of the stereo-laparoscope may well be possible without significant loss of stereoscopic benefits. A 25% reduction would seem not to entail much loss at all and even a 50% reduction would leave significant stereoscopic benefits.

These observations, however, need to be replicated with a more complete realization of the stereoscopic conditions of a reduced camera baseline as could be produced with a precision, miniaturized, optical mechanism.

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