Effectiveness of Naked-eye Vision Feedback for Training Human Teleoperators

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Abstract

Effective training is essential for human teleoperators to deliver satisfactory performance in actual tasks. Teleoperation is naturally a very difficult task due to the absence of naked-eye vision that cripples the cognitive behavior of the remote operator. Camera vision somehow is not a satisfactory substitution. However, training with naked-eye vision feedback may help human teleoperators to learn how to deliver satisfactory performance when they actually interact with camera vision. This study was carried out to further investigate this hypothesis, and to quantitatively supplement it with experimental proofs. For this cause, the recently built telerobotic test-bed between KAIST(Korea) and Saga University(Japan) was reshaped to a telerobotic mini-golf system, which is the trial experiment in this study. The performance of the players with and without naked-eye training was compared and quantitatively evaluated. The effectiveness of training with naked-eye vision was verified as an essential part in training human teleoperators.

1 Introduction

Teleoperation and telerobotics are now on its second phase of development [1],[2],[3], stimulated by the proliferation of the Internet. Beyond the specialized classical applications in space [4], undersea [5], and nuclear industry, teleoperation is now becoming a more general means for many applications such as medical [6], welfare [7], rescue [8], and entertainments [9]. The stability problem caused by transmission delay has been thoroughly analyzed and almost solved [10], [11] by introducing supervisory control. The visual feedback is the other crucial problem that cripples most of the performances in teleoperation. Graphics based visual monitoring systems such as virtual reality [12] and telepresence [13] have been proposed to provide the teleoperator with as much visual information as possible, at a cost of excessive graphics processing overhead.

Although efforts are taken to develop sophisticated systems, it seems that there has not been a thorough investigation to understand and describe how the human operator cognitively interact with the telerobot [14], and his learning and adaptation patterns. Such information might provide very important clues to develop telerobotic systems and training procedures for teleoperators so that to exploit the cognitive behavior of humans in teleoperation.

Training of human teleoperators is also very important. Proper training should harness the cognitive capabilities in actual tasks with the available vision feedback. Training with naked-eye vision would provide the required experience and learning for the teleoperator so that he would perform well in actual tasks by interacting with the available vision feedback. This hypothesis is to be experimentally tested in this work.

For this purpose, the telerobotic test-bed between KAIST(Korea) and Saga University(Japan) was reshaped to a simple, yet challenging telerobotic golf system. Nine players, in two groups, played telerobotic golf producing valuable experimental data. The Saga University group played three trials each with naked-eye vision and another three trials each with camera vision. The KAIST players played tree trials each with the camera vision. Their performances were evaluated by analyzing interactive actions, errors and time consumption. Errors and time consumption of the two groups clearly verified that training with naked-eye vision is a very effective pre-requisite for teleoperators. As most telerobots can be teleoperated with naked-eye vision, before they are actually deployed to worksites, this training procedure it practically realizable.

2 The Telerobotic Golf Game

2.1 Telerobotic Test-bed

A new telerobotic test-bed has been built between KAIST(Korea) and Saga University(Japan). The remote operator terminal resides in KAIST, and the local controller and telerobot reside in Saga University(Japan). The two sides communicate through TCP sockets over the Internet. Remote operator terminal reads motion commands that are issued by the golfer on his keyboard, and sends those commands to the local controller in Saga University. The local controller runs a non real-time process, which reads those position commands, and calculates the distance of putter motion. This incremental motion is locally planned assuming uniform putter speed. Local controller also runs a real-time process, which executes the feedback control of the telerobot. It reads motion data from the non-real time process described above. A complete account on the KAIST-Saga University telerobotic test-bed and its design features can be found in [15]

2.2 Design Features of Telerobotic Golf System

By way of task oriented design, the telerobotic test-bed was customized to a telerobotic golf system as shown in Figure 1(a). The key design features are explained as follows:

2.2.1 Putter Design: The putter was designed as shown in Figure 1(b), with a thin long handle terminating at 1[cm] thick, square shaped piece of wood. The handle is sufficiently thin so that it does not block the view of the ball and the hole during the play. The dimensions of the square shaped end are sizable so that its positioning is not required to be precise before putting the ball. The thickness of the tool is small enough so that it always contacts the ball close to the ground, thereby, avoiding unnecessary force on the ground. This feature also provides more rolling torque, which facilitates motion. Figure 1(c) shows the forces acting on the ball when it is in contact with the putter, which is held closer to the ground. The rolling torque $\tau = Fr\cos\beta$, where F is the contact force on the ball,

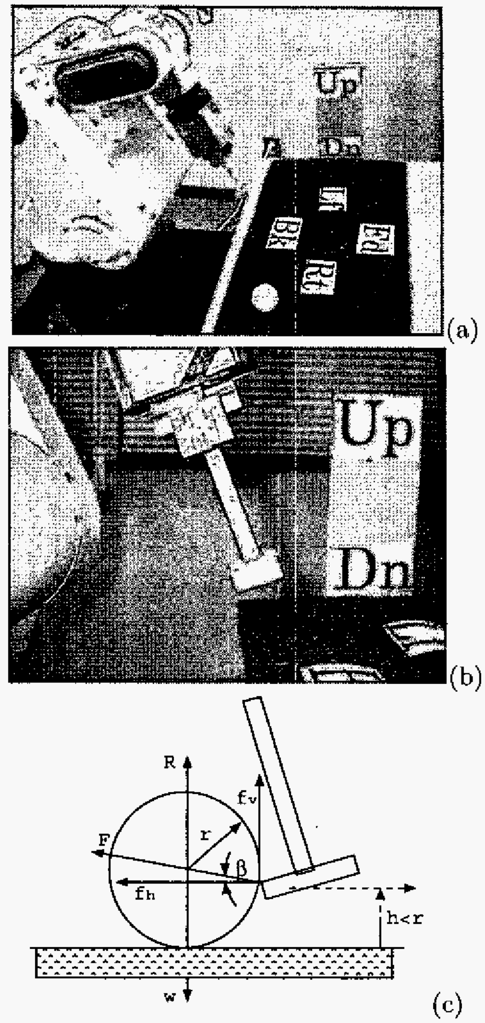

Figure 1: Telerobotic golf: (a) The golf court, (b) Putter design, and (c) Force diagram of the putting stroke

r is the radius of the ball, and $\beta = \sin^{-1}(r-h)/r$; $h < r$ being the height of the contact point from the ground. If the condition $h < r$ is satisfied, the reaction force at the contact point of the ball and the ground is $R = w - f_v$, where w is the weight of the ball and $f_v = F\sin\beta$ is the vertical component of F. This condition helps ball movement along the ground.

2.2.2 Control System Design: The industrial manipulator shown in Figure 1(a) has five degrees of freedom in R-R-R-R-P configuration. The first joint has a vertical axis of rotation, whereas next three joints have horizontal axes of rotation. In the telerobotic golf design, only the first three joints were used. All three joints are rate controlled in joint co-ordinates $(\theta_1, \theta_2, \theta_3)$ in response to a motion command in Cartesian co-ordinates (x, y, z). The inverse kinematic transformation is given by

$$\theta_1 = \tan^{-1}(y/x) \quad (1)$$

$$\theta_2 = \tan^{-1}(c/z) - \cos^{-1}\left[\frac{L_2^2 - L_3^2 + c^2 + z^2}{2L_2\sqrt{c^2+z^2}}\right] \quad (2)$$

$$\theta_3 = \pi - \cos^{-1}\left[(L_2^2 + L_3^2 - c^2 - z^2)/(2L_2L_3)\right] \quad (3)$$

where $c = \sqrt{x^2+y^2} - L_1$, and L_j is the length of jth link. Independent servo actuators implement the feedback control law $u^j = K_v \left\{Kp(\theta^j_{in} - \theta^j_{out}) - \dot{\theta}^j_{out}\right\}$, where θ^j_{in}, θ^j_{out}, $\dot{\theta}^j_{out}$ are position input, position output, and velocity output of jth joint. Parameters K_p and K_v are position and velocity feedback gains. And, u^j is the power amplifire current input.

2.2.3 Constraint Checking and Safety Assurance:

Having to deal with priori unknown maneuvers, telerobotic golf system requires thorough constraint checking of the remote operator position commands. All maneuverability constraints can be categorized into three groups as follows:

Joint limits : All rotary joints have their working ranges. Once the remote operator command is transformed into joint co-ordinates using (1), (2), and (3). Joint positions are checked to verify that they remain within their respective working ranges $[\theta^j_{limit-}, \theta^j_{limit+}]; j = 1, 2, 3$.

Maximum reach : First joint is a vertical axis joint, thus, can be eliminated from the calculation of tool reach. The maximum stretch of the manipulator with respect to the second joint is $L2 + L3$. And, if the remote operator command (x, y, z) satisfies $L2 + L3 - \sqrt{(\sqrt{x^2+y^2} - L_1)^2 + z^2} < \delta$, then, for any arbitrary command (x, y, z), the manipulator is safe from a distance of δ from the full-stretch singularity.

Minimum putter height : The putter should always stay above the ground height h_{ground}. If the constraint $z > h_{ground}$ is satisfied, it is guaranteed that the putter does not come in contact with the ground.

All these constraints are checked at the remote operator terminal. Once all checks are passed, the command is sent to the local controller. This way, the safe operation of the telerobotic golf game is assured.

2.2.4 Remote Operator Interface:

A keyboard interface was selected as it is the most common computer peripheral, which can be used as a teleoperator interface. This way, the telerobotic game could be played by anyone from anywhere in the world through his keyboard, after logging into the remote operator terminal in KAIST. The keys were assigned as shown in Figure 2 to be consistent with the motion directions of the putter shown in Figure 1(a).

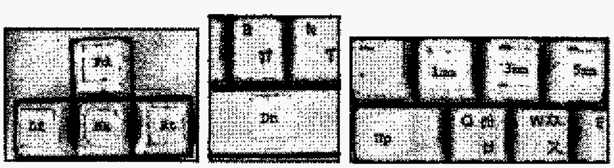

Figure 2: Teleoperator's keyboard configuration

The key assignment is as follows The four arrow keys were assigned to X-Y motion as ↑(+X:Forward), ↓(-X:Backward), ←(+Y:Left), and →(-Y:Right). Vertical motion was assigned to "tab" key(+Z:Up), and "space bar"(-Z:Down). The numeric keys 1, 2, and 3 assigned for step lengths of 1[mm], 3[mm], and 5[mm], respectively. This key assignment was purely arbitrary, based on intuition. One rationale however is that this configuration is consistent with the natural finger positioning on the standard computer keyboard.

2.3 Challenges for the Teleoperator

There are few difficulties that challenge the teleoperator who plays telerobotic-golf.

Putter orientation : Putter is an extension of the prismatic fifth link, and the telerobot is operated using the first three joints. Having no motion at the fourth rotary joint, putter remains fixed at the same joint position relative to the third link. However, to assist the teleoperator, the fourth link is pre-adjusted to an approximate average vertical configuration within the golf-court. The prismatic fifth joint is also not operated, and it avoids the teleoperator rotate the putter the way he prefers.

Diagonal motions : Remote operator commands are limited to individual motions along X-Y-Z directions. There is no way to make other movements that combines those individual motions.

2D visual feedback : Visual feedback provides only 2D view of the golf-court at a fixed camera position. It does not provide direct information of the relative putter position. And, no control of the camera positioning is provided.

2.4 Implementation

The remote operator terminal was implemented on Red-Hat Linux 8.0 with kernel version 2.4.20-19.8. The local controller was implemented on Debian GNU Linux 3.0, with real-time kernel 2.4.4-rtl. Due to network security reasons, local controller has not been assigned a global IP address, but it runs a virtual private network that issues a local IP address for the remote operator terminal. The visual feedback was implemented with Microsoft Net-meeting utility, with a single, inexpensive web-camera located at the telerobotic golf-court. Teleoperator's keyboard commands are checked against the working range of joints [-152,152](joint 1), [-45,140](joint 2), and [-142.5,142.5](joint 3) before sending to the local controller.

3 The Experiment

There were nine players involved; five from KAIST and four from Saga University. They were explained that the operation was safe on their possible wrong commands, and that they were expected to reach the goal as quickly as possible, while learning by mistakes. Their courses of actions were recorded as movie clips, replayed, and evaluated. Saga University players were named as S1, S2, S3, and S4, whereas KAIST players were named as K1, K2, K3, K4, and K5. The experiment had three steps; (a) Saga players played three trials each with naked-eye vision, by login to the remote operator terminal at KAIST, (b) After (a), Saga players played the same game with the camera vision, (c) KAIST players played three trials each with camera vision, without any prior training with naked-eye vision.

3.1 Evaluation Criterion

The evaluation criterion was developed on the following error measures:

1. E1: Hole error: If the player had to significantly change the direction of motion at the close vicinity of the hole, it is judged as a hole error.
2. E2: Landing error. If the player had to make many moves off the ground before landing the putter behind the ball, it is judged as a landing error.
3. E3: Steering error: If the player failed to keep putting the ball from behind, it is judged as a steering error

Errors are further evaluated and tagged as "-"(slight), "no sign"(considerable), and "+"(serious). This grading was carried out by inspection of the movie clips. Errors were further converted to numerical form by the marking them with 1 point (slight errors), 2 points (considerable errors), and 3 points (serious errors).

3.2 Results

The putter motions of Saga University players are shown in Figure 3, at the last trial with naked-eye vision and the first trial with camera vision. The error counts and timing of Saga University players in experimental steps (a) and (b) are given in TABLE I. The same statistics for KAIST players in experimental step (c) is given in TABLE II. The error counts and timing are graphed in Figure 4(a), (b), and (c) for the corresponding experimental steps.

The results can be interpreted as follows:

1. In Figure 3 the putter motions at the last trial with naked-eye vision are comparable to the first trial with camera vision. It indicates that the training with the naked-eye vision is carried into the trials with the camera vision.
2. Results in Figure 4 clearly indicate that error level and timing of step (b) is in between step (a) and step (c). It verifies the hypothesis that the errors and time consumption can be reduced by undergoing a few trials with naked-eye vision.
3. The ↓ in Figure 4(a) indicates a highly unlikely performance, where the timing in the third trial of S1 player increases up to 86[s]. In the movie clip, it was noticed that the cause was a local defect on the golf-court. As to compensate this error, the timing of this trial was re-adjusted to the average of the first and second trials, i.e. 58[s]. After this adjustment, the average time consumptions were determined for (a), (b), and (c) steps as 60[s], 67[s], and 72[s]. It indicates clearly that the naked-eye training has reduced the operator time by 5[s].
4. Figure 5 shows gradual improvement of putter motion of player S3 despite the visual feedback changed from naked-eye vision to camera vision. All other players exhibited similar behavior in their trials. The trial sequence is horizontal from left to right.

Following related observations have also been made.

1. Although the two-dimensional camera vision does not provide adequate feedback information for the teleoperator, he is capable of learning quickly by experience and guess-work. Practice with naked-eye vision significantly helps human teleoperator to accurately conceive the work-site geometry and also to exercise predictive control actions when he deals with camera vision.
2. The round trip transmission delay was measured by a "ping-test" as 14[ms]/20[ms]/28[ms] in the minimum/average/mean deviation format. Visual feedback adds more time to these statistics. This delay has been slightly noticed by almost all players. Yet, they did not experience any difficulty in practicing their predictive control actions.
3. Predictive control is attributed to teleoperation. As predictive control is based on the velocity of motion, it is necessary to maintain a continuous motion to exploit cognitive prediction skills of the teleoperator. It was clearly observed that many operators prefer to use small step lengths (1[mm]-3[mm]) and keep issuing commands and maintain a velocity throughout the operation. On the other hand, they dislike move-and-wait mode of control as waiting significantly retards their predictive control capabilities.
4. More crucial factor that consumes time is wrong commands due to wrong key strokes. All players demonstrated this confused interaction with the keyboard intermittently. However, with more appropriate key assignment, and also with practice, this problem can be completely solved.

4 Conclusion

This experimental study suppliments the generally known fact that humans learn by errors and adapt very quickly to interact with complex systems such as a telerobotic infterface. It has been quatitatively verified that a very few experimental trials is enough to learn and avoid errors even without sophisticated graphics-based interfaces. Most teleoperators show a consistent pattern of performance improvement. Although two-dimensional camera visual feedback significantly affects teleoperator performance, training with naked-eye vision significantly helps them in interacting with camera vision in actual teleoperations, and also to make use of their cognitive behavior. Keyboard interface has shown to be very effective and easy to train with, as it provides the operator a quantitative measure about his own commands. It helps the teleoperator to predict the movements of the telerobot more accurately. It is also concluded that small step sizes and more continuous motions are effective to exploit the cognitive behavior of human teleoperators.

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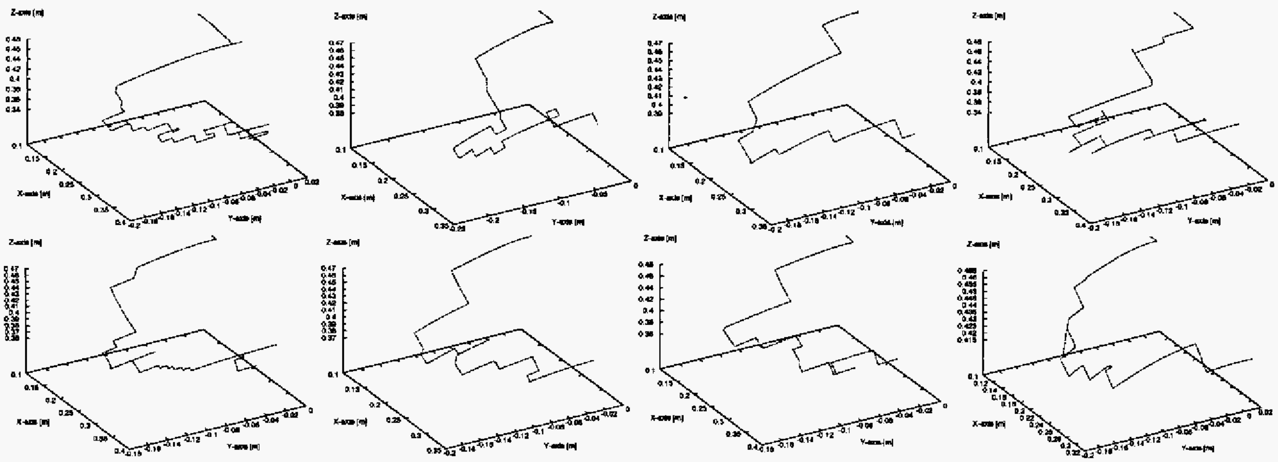

Figure 3: Trajectories at the visual feedback switching: Top - last trial with naked-eye visual feedback, Bottom - first trial with camera feedback

TABLE I : Error and timing statistics for Saga University players in step (a) and (b)

Naked-eye visual feedback

	Errors (E1,E2,E3), and timing (t)		
Player	Trial #1	Trial #2	Trial #3
S1	(E1,E2,E3), (80)	(0,0,E3), (37)	(E1,0,E3+), (86)
S2	(0,E2+,E3+), (73)	(0,0,E3), (47)	(0,0,E3), (50)
S3	(E1,E2,E3), (78)	(E1,0,E3), (46)	(E1,0,E3-), (36)
S4	(E1,E2,E3+), (86)	(0,E2+,E3+), (60)	(0,E2+,E3+), (65)

Camera visual feedback

	Trial #1	Trial #2	Trial #3
S1	(E1,0,E3), (90)	(E1,0,0), (80)	(0,0,0), (80)
S2	(0,0,E3), (61)	(0,0,E3-), (37)	(0,0,0), (36)
S3	(0,0,E3), (97)	(0,0,E3), (63)	(0,0,0), (58)
S4	(0,E2-,E3+), (71)	(0,E2-,E3+), (81)	(0,0,E3), (52)

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TABLE II : Error and timing statistics for KAIST players in step (c)

player	Errors (E1,E2,E3), and timing Trial #1	Trial #2	Trial #3
K1	(0,0,0), (66)	(0,0,E3), (75)	(E1,0,0), (55)
K2	(0,E2-,0), (116)	(0,0,0), (59)	(0,0,0), (52)
K3	(E1,E2+,E3+), (105)	(0,E2,0), (68)	(0,E2-,0), (59)
K4	(E1,E2+,E3), (103)	(0,E2,E3), (51)	(0,E2-,E3), (49)
K5	(E1,E2+,E3), (101)	(0,0,0), (57)	(0,0,E3), (71)

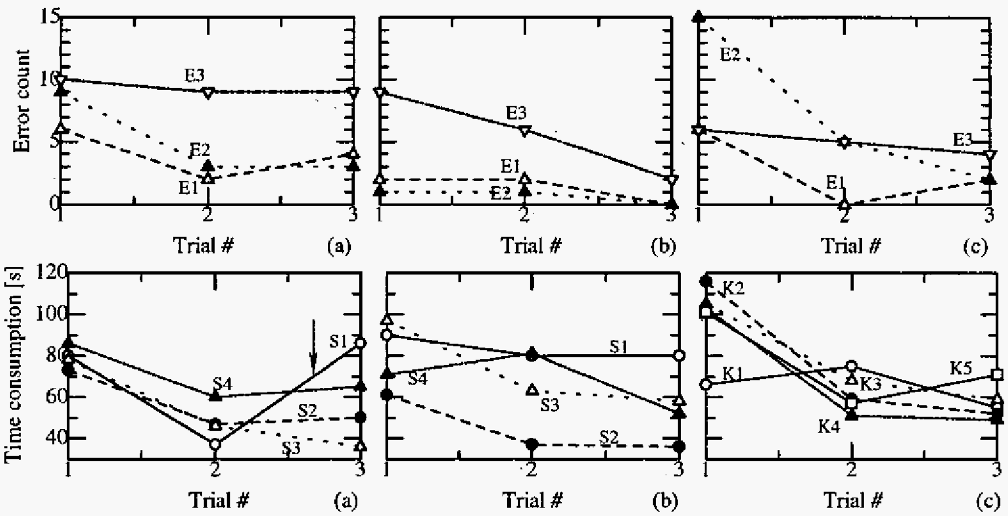

Figure 4: Error counts and timing (a) with naked-eye vision, (b) with camera vision, after naked-eye training, and (c) with camera vision, without any prior naked-eye training

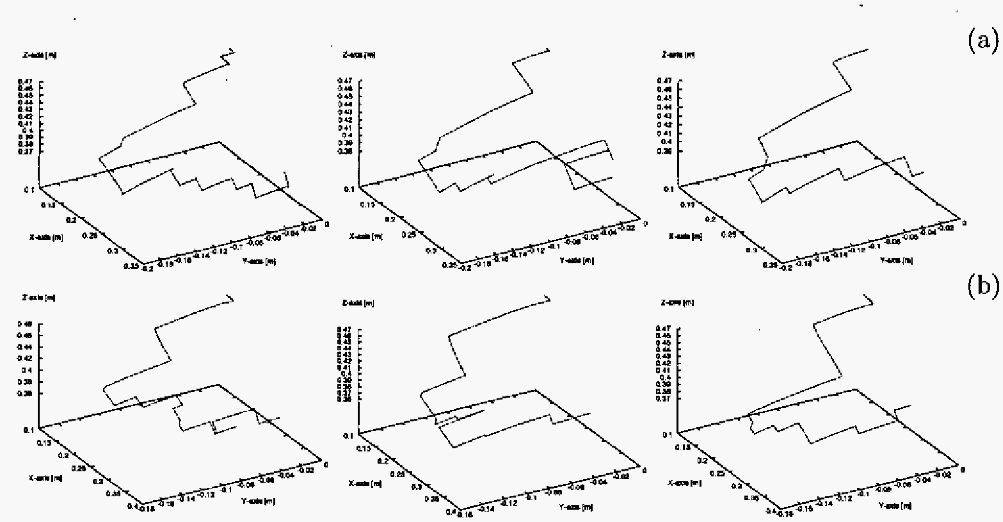

Figure 5: The six trials of player S3: (a) with naked-eye vision, and (b) with camera vision