Collaborative Teleoperation Using Networked Spatial Dynamic Voting

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Invited Paper

We describe a networked teleoperation system that allows groups of participants to collaboratively explore live remote environments. Participants collaborate using a spatial dynamic voting (SDV) interface that allows them to vote on a sequence of images via a network such as the Internet. The SDV interface runs on each client computer and communicates with a central server that collects, displays, and analyzes time sequences of spatial votes. The results are conveyed to the "tele-actor," a skilled human with cameras and microphones who navigates and performs actions in the remote environment. This paper formulates analysis in terms of spatial interest functions and consensus regions, and presents system architecture, interface, and algorithms for processing voting data.

Keywords**—***Human interface, Internet, Internet robot, multiple-operator single-robot (MOSR) teleoperation, networked robot, on-line robot, tele-actor, teleoperation, telerobot, telerobotics, voting.*

I. INTRODUCTION

Consider the following scenario: an instructor wants to take a class of students to visit a research lab, semiconductor plant, or archaeological site. Due to safety, security, and liability concerns, it is impossible to arrange a class visit. Showing a prerecorded video does not provide the excitement or group dynamics of the live experience. In this paper, we describe a system that allows groups to collectively visit remote sites using client-server networks. Such "collaborative teleoperation"' systems may be used for applications in education, journalism, and entertainment.

Remote-controlled machines and teleoperated robots have a long history [60]. Networks such as the Internet provide low-cost and widely available interfaces that makes such resources accessible to the public. In almost all existing teleoperation systems, a single human remotely controls a single machine. We consider systems where a group of humans shares control of a single machine. In a taxonomy proposed by Tanie *et al.* [12], these are multiple-operator single-robot (MOSR) systems, in contrast to conventional single-operator single-robot (SOSR) systems.

In MOSR systems, inputs from many participants are combined to generate a single control stream. There can be benefits to collaboration: teamwork is a key element in education at all levels [13], [14], [57], and the group may be more reliable than a single (possibly malicious) participant [25].

As an alternative to a mobile robot, which can present problems in terms of mobility, dexterity, and power consumption, we propose the *tele-actor*, a skilled human with cameras and microphones connected to a wireless digital network, who moves through the remote environment based on live feedback from on-line users.

We have implemented several versions of the system. Fig. 1 shows a view of the spatial dynamic voting (SDV) interface implemented for Internet browsers. Users are represented by "votels": square colored markers that are positioned by each user with a mouse click. This paper presents problem formulation, system architecture and interface, and algorithms for processing voting data.

II. RELATED WORK

Goertz demonstrated one of the first bilateral simulators in the 1950s at the Argonne National Laboratory, Argonne, IL [23]. Remotely operated mechanisms have long been desired for use in inhospitable environments such as radiation sites, under the sea [4], and space exploration [6]. At General Electric, Mosher [49] developed a complex two-arm teleoperator

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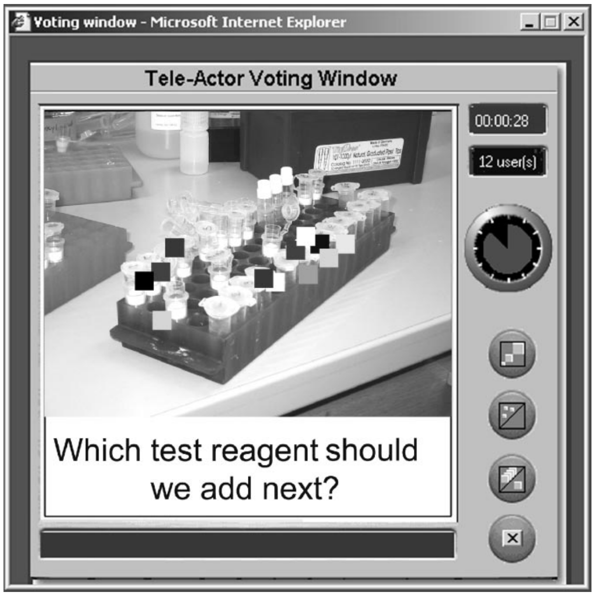

Which test reagent should we add next?

Fig. 1. The SDV interface as viewed by each user. In the remote environment, the tele-actor takes images with a digital camera which are transmitted over the network and displayed to all participants with a relevant question. With a mouse click, each user places a color-coded marker (a "votel" or voting element) on the image. Users view the position of all votels and can change their votel positions based on the group's response. Votel positions are then processed to identify a "consensus region" in the voting image that is sent back to the tele-actor. In this manner, the group collaborates to guide the actions of the tele-actor.

with video cameras. Prosthetic hands were also applied to teleoperation [62]. More recently, teleoperation is being considered for medical diagnosis [5], manufacturing [22], and micromanipulation [59]. Sheridan [60] provides an excellent review of the extensive literature on teleoperation and telerobotics.

Networked robots, controllable over networks such as the Internet, are an active research area. In addition to the challenges associated with time delay, supervisory control, and stability, on-line robots must be designed to be operated by nonspecialists through intuitive user interfaces and to be accessible 24 hours a day.

The Mercury Project was the first publicly accessible networked robot [26], [27]; it went on-line in August 1994. Working independently, a team led by K. Taylor and J. Trevelyan at the University of Western Australia, Crawley, Australia, demonstrated a remotely controlled six-axis telerobot in September 1994 [15], [33]. There are now dozens of Internet robots on-line, a book from MIT Press [29], and an IEEE Technical Committee on Internet and Online Robots. See [32], [34]–[36], [38], [40], [48], [50], [58] for examples of recent projects.

Tanie *et al.* [12] proposed a useful taxonomy for teleoperation systems: SOSR, single-operator multiple-robot (SOMR), and multiple-operator multiple-robot (MOMR).

Most networked robots are SOSR, where control is limited to one human operator at a time. Tanie *et al.* analyzed an MOMR system where each operator controls one robot arm and the robot arms have overlapping workspaces. They show that predictive displays and scaled rate control are effective in reducing pick-and-place task completion times that require cooperation from multiple arms [12].

In an MOMR project by Elhajj *et al.* [17], [18], two remote human operators collaborate to achieve a shared goal such as maintaining a given force on an object held at one end by a mobile robot and by a multijointed robot at the other. The operators, distant from the robots and from each other, each control a different robot via force feedback devices connected to the Internet. The authors show both theoretically and experimentally that event-based control allows the system to maintain stable synchronization between operators despite variable time lag on the Internet.

MOMR models are also relevant to on-line collaborative games such as *Quake* and *The Sims Online*, where players remotely control individual avatars in a shared virtual environment.

In SOMR systems, one human operator controls multiple robots. A variant is no-operator multiple-robot (NOMR) systems, sometimes called collaborative or cooperative robotics, where groups of autonomous robots interact to solve an objective [2]. Recent results are reported in [9], [16], [54], and [56].

A number of SOSR systems have been designed to facilitate remote interaction. Paulos and Canny's Personal Roving Presence (ProP) telerobots, built on blimp or wheeled platforms, were designed to facilitate remote social interaction with a single remote operator [51], [52]. Hamel [31] studied how networked robots can be useful in hazardous environments. Fong *et al.* study SOSR systems where collaboration occurs between a single operator and a mobile robot that is treated as a peer to the human and modeled as a noisy information source [20]. Related examples of SOSR "cobots" are analyzed in [1], [7], [41], [44], [45], and [61].

One precedent for an on-line MOSR system is described in McDonald *et al.* [46]. For waste cleanup, several users assist remotely using point-and-direct (PAD) commands [10]. Users point to cleanup locations in a shared image and a robot excavates each location in turn. In this Internet-based MOSR system, collaboration is serial but pipelined, with overlapping plan and execution phases. The authors demonstrate that such collaboration improves overall execution time, but do not address conflict resolution between users.

Pirjanian studies how reliable robot behavior can be produced from an ensemble of independent processors [53]. Drawing on research in fault-tolerant software [39], Pirjanian considers systems with a number of homogenous processors sharing a common objective. He considers a variety of voting schemes and shows that fault-tolerant *behavior fusion* can be optimized using plurality voting [8], but does not consider spatial voting models such as ours.

In [24], we present an Internet-based MOSR system that averaged multiple vector inputs to control the position of an industrial robot arm. We report experiments with maze following that suggested that groups of humans may perform better than individuals in the presence of noise due to central limit effects.

In [25], we used finite automata to model collaborating users in a MOSR system such as Cinematrix, a commercial

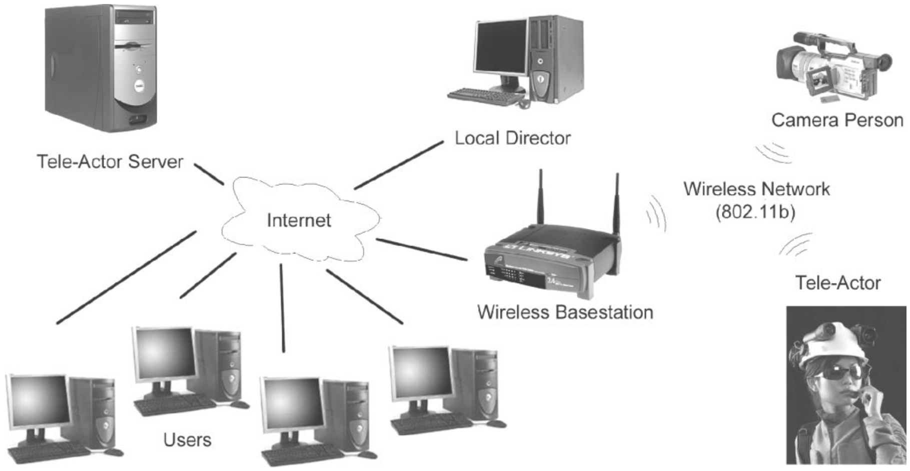

Fig. 2. System architecture. Participants on the Internet view and voting on a series of voting images. The human tele-actor, with head-mounted wireless audio/video link, moves through the remote environment in response. The "local director" facilitates interaction by posting textual queries.

system [11] that allows large audiences to interact in a theater using plastic paddles. To model such systems, we averaged an ensemble of finite automata outputs to compute a single stream of incremental steps to control the motion of a point robot moving in the plane. We analyzed system performance with a uniform ensemble of well-behaved deterministic sources and then modeled malfunctioning sources that go silent or generate inverted control signals. We found that performance is surprisingly robust even when a sizable fraction of sources malfunction.

Outside of robotics, the notion of MOSR is related to a very broad range of group activities including social psychology, voting, economics, market pricing, traffic flows, etc. The Association for Computing Machinery organizes annual conferences on computer-supported collaborative learning and computer-supported cooperative work. Surveys of research in this broader context can be found in [3], [19], [21], [28], [37], [47], and [55].

We note that the concept of human-mounted cameras with network connections is not novel: there is extensive literature on "wearable computer" systems [42], [43]. The focus of our research is on collaborative control. A preliminary report on the tele-actor system appeared in [30].

III. SYSTEM ARCHITECTURE

The tele-actor system architecture is illustrated in Fig. 2. As the tele-actor (see Fig. 3) moves through the environment, camera images are sent to the tele-actor server for distribution to users, who respond from their Internet browsers. User voting responses are collected at the tele-actor server, which updates Java applets for all users and for the tele-actor in the field. The tele-actor carries a laptop which communicates to the Internet using the 2.4-GHz 802.11b wireless protocol. A cameraperson with a second camera provides third-person perspectives as needed. Using this architecture, the users, the tele-actor server, the local director, the cameraperson, and the tele-actor communicate via the Internet.

Fig. 3. The human tele-actor transmits images from the remote environment using the helmet-mounted video camera and responds to user votes. Helmet design by E. Paulos, C. Myers, and M. Fogarty. (Photo by B. Nagel.)

IV. SDV USER INTERFACE

We have developed a new graphical interface to facilitate interaction and collaboration among remote users. Fig. 1 illustrates the SDV interface that is displayed on the browser

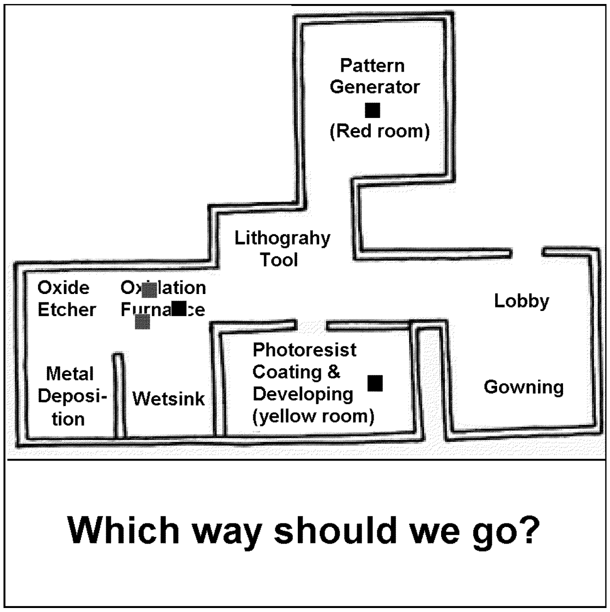

Fig. 4. Navigation query. Participants indicate where they want the tele-actor to go.

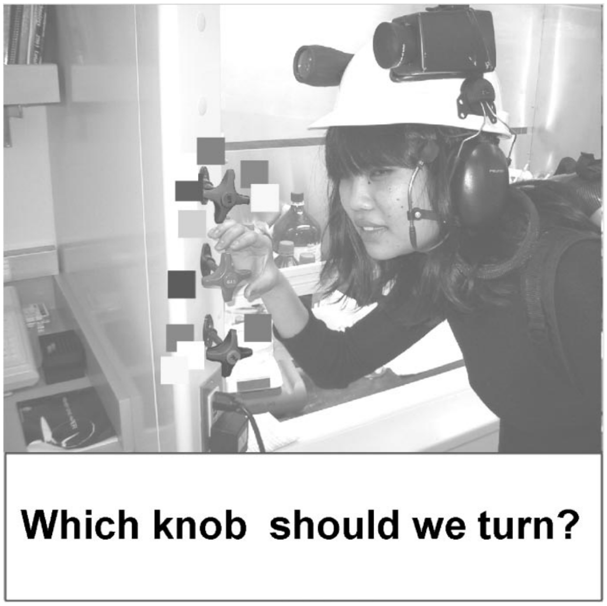

Fig. 5. Point query. Participants point out a region of interest in the voting image.

of all active voters. Users register on-line to participate by selecting a votel color and submitting their e-mail address to the tele-actor server, which stores this information in our database and sends back a password via e-mail. The server also maintains a tutorial and a FAQ section to familiarize new users with how the system works.

Using the SDV interface, voters participate in a series of 30- to 60-s voting images. Each voting image is a single image with a textual question. In the example from Fig. 1, the tele-actor is visiting a biology lab. Voters click on their screens to position their votels. Using the HTTP protocol, these positions are sent back to the tele-actor server and appear in an updated voting image sent to all voters every 3–5 s. In this way, voters can change their votes. When the voting cycle is completed, SDV analysis algorithms analyze the voting pattern to determine a consensus command that is sent to the tele-actor. The SDV interface differs from multiple-choice polling because it allows spatially and temporally continuous inputs.

To facilitate user training and asynchronous testing, the tele-actor system has two modes. In the off-line mode, voting images are drawn from a prestored library. In the on-line mode, voting images are captured live by the tele-actor. Both off-line and on-line modes have potential for collaborative education, testing, and training. In this paper, we focus on the on-line mode.

Figs. 4–7 illustrate four types of SDV queries and their associated branching structures. In each case, the position of the majority of votels decides the outcome.

We tried including a live video broadcasting stream but found that due to bandwidth limitations, the resolution and frame rate is unacceptable for low-latency applications. Standard video broadcasting software requires about 20 s of buffered video data for compression, which introduces unacceptable delays for live visits. We are hoping this can be reduced in the future with faster networks such as Internet2.

V. HARDWARE AND SOFTWARE

The tele-actor Web server is an AMD K7 950-MHz PC with 1.2-GB memory connected to a 100-Mb/s T3 line. The Video server is also an AMD K7 950-MHz PC with 512-MB memory connected to a 100-Mb/s T3 line. The local base station could be any machine on the Internet equipped with Java-enabled Web browsers. The primary tele-actor is carrying a 600-MHz Sony picture-book laptop with 128-MB memory connected to a 11-Mb/s 802.11b wireless LAN at the remote site. It has a USB video card, which captures video at 320 × 240 resolution. The cameraperson has a Pentium III 750-MHz Sony Vaio laptop with 256-MB memory with similar USB video capture device. The laptops direct their video displays to hand-mounted TVs to provide updates on voting patterns. Fig. 2 shows that the primary tele-actor has a Canon camera mounted on her helmet. Fig. 8 shows that the cameraperson has a Sony camcorder with night vision capability, which provides very high-quality image and video stream. Both of them are equipped with a shutterlike device to allow them to capture the precious moment in the live event.

Custom software includes: 1) the client-side SDV browser interface based on Java; 2) the tele-actor image capture and communication software; 3) the local base station voting question formulation interface; and 4) the tele-actor server. During the on-line mode, the local director uses a Java applet to add textual questions to voting images.

During both on-line and off-line modes, the tele-actor server uses custom C and C++ applications to maintain the database and communicate with the local base station and with all active voters. The tele-actor server runs Redhat Linux 7.1 and the Apache Web server 1.3.20. The Resin

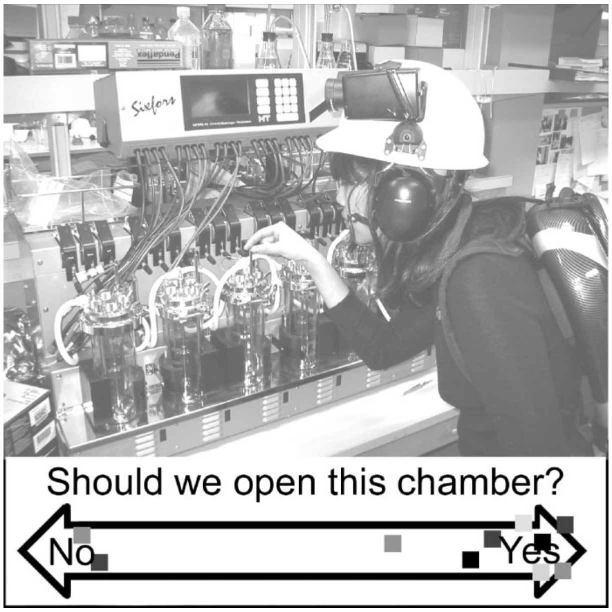

Fig. 6. Opinion query. Votel position can be anywhere between extreme values to indicate degree of opinion.

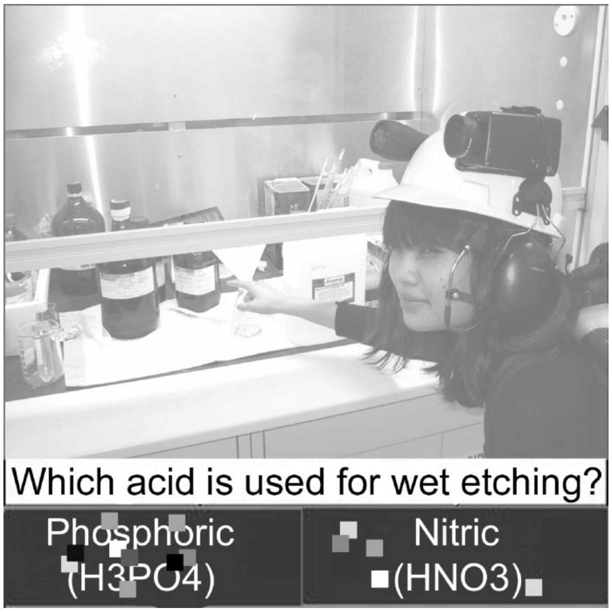

Fig. 7. Multiple-choice query. A variation on the point query with a small number of explicit options.

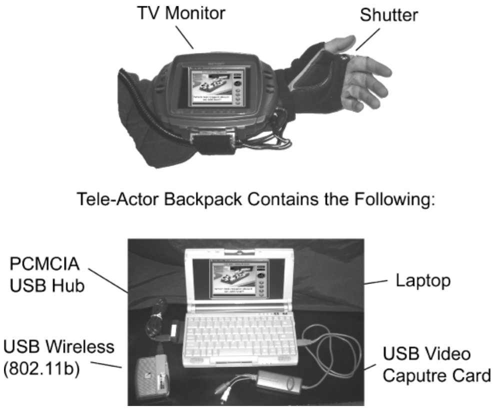

Fig. 8. Hardware configuration for the cameraperson. The hardware configuration of the tele-actor is similar but has a helmet-mounted camera.

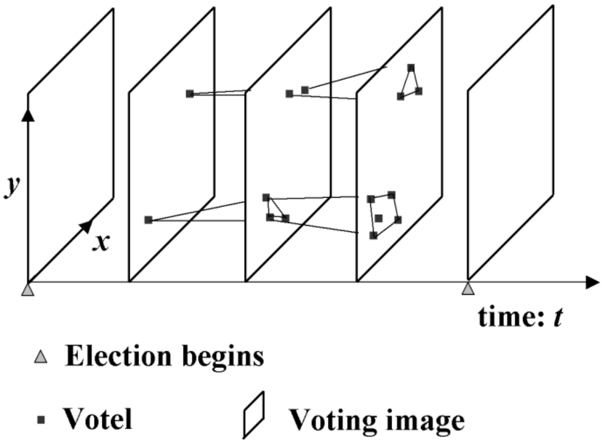

Fig. 9. Evolution of voting image as votels arrive.

2.0.1 Apache plug-in and Sun JDK 1.3.1 with Mysql database 3.23.36 provide Java server pages to handle the user registration and data logging.[1]

VI. PROBLEM DEFINITION AND ALGORITHMS

As illustrated in Fig. 9, users express responses by clicking on the voting image to spatially indicate a preferred object or direction in the field of view. As an alternative to semantic analysis of the voting image, we consider votels as spatial distributions and identify preferred "consensus" regions in the image. We then use these regions to define two metrics for individual and group performance in terms of leadership and collaboration.

A. Problem Definition

1) Voter Interest Functions: Consider the kth voting image. The server receives a response from user i in the form of an (x, y) mouseclick on image k at time t. We define the corresponding *votel*: $v_{\mathrm{ik}}(t) = [x_{\mathrm{ik}}(t), y_{\mathrm{ik}}(t)]$.

Each votel represents a user's response to the voting image. We model such responses with a *voter interest function*, a density function based on the bivariate normal distribution

$$f_{\mathrm{ik}}(x, y) \sim N(v_{\mathrm{ik}}(t), \Sigma_{\mathrm{ik}}(t))$$

where $v_{\mathrm{ik}}(t)$ is the mean vector and $\Sigma_{\mathrm{ik}}(t)$ is a 2×2 variance matrix, such that

$$\int\int_{\sigma} f_{\mathrm{ik}}(x, y)\, dx\, dy = 1$$

where σ is the area of the voting image. Since σ is a bounded two-dimensional region, the voter interest function is a truncated bivariate normal density function with mean at $v_{\mathrm{ik}}(t)$, as illustrated in Fig. 10.

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[1] [Online] Available: http://www.caucho.com

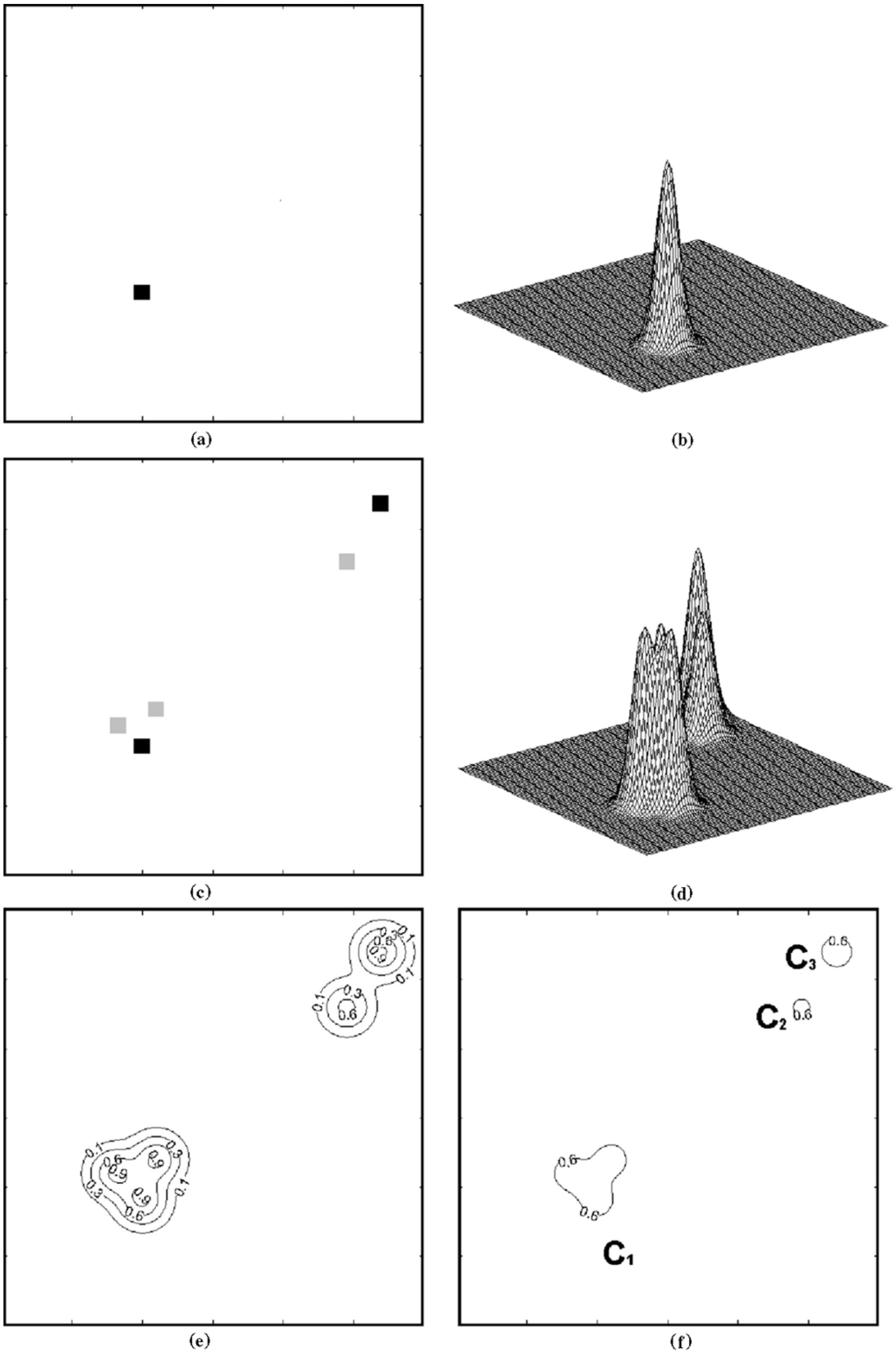

Fig. 10. Interest functions and consensus regions. (a) and (b) show the interest function for a single voter. (c) and (d) show an ensemble interest density function for five voters. (e) and (f) illustrate resulting consensus regions.

2) Ensemble Interest Function: When voting on image k ends at stopping time T, the last votel received from each of n active voters determines V_k, a set of n votels. We define the *ensemble interest function* for voting image k as the normalized sum of these voter interest functions

$$f_k(x, y) = \frac{1}{n} \sum_{i=1}^{n} f_{\mathrm{ik}}(x, y).$$

3) Consensus Regions: We can extract spatial regions from the ensemble interest function as follows. Let

$$f_k^* = \sup f_k(x, y)$$

be the maximum of the ensemble interest density function, and let r be some value between 0 and 1. A horizontal plane at height $r f_k^*$ defines an isodensity contour in the ensemble interest function that defines a set of of one or more closed subsets of the voting image

$$S_k = \{(x, y) | f_k(x, y) \geq r f_k^*\}.$$

Table 1
SDV Analysis of Voting Image From Fig. 11

C_{jk}	Interval	Width	#Votes	D_{kj}
1	[52, 94]	42	8	2.26
2	[139, 180]	51	5	1.16
3	[236, 288]	52	14	3.19
Overall	–	145	27	2.21

Intervals and widths are in pixels.

As illustrated in Fig. 10, we refer to these subsets as *consensus regions*

$$S_k = \{C_{1k}, C_{2k}, \ldots, C_{mk}\}.$$

Since there are n voters, $m \leq n$.

Given $V_k = \{v_{\mathrm{ik}}(T)\}$, $i = 1, \ldots, n$, ratio r, and variance matrix function $\Sigma_{\mathrm{ik}}(T)$, we can compute the consensus regions S_k.

B. Ensemble Consensus Region

Given S_k, V_k, the *ensemble consensus region* is a region with the most votels. Let

$$I_k(i,j) = \begin{cases} 1, & \text{if } [x_{\mathrm{ik}}(T), y_{\mathrm{ik}}(T)] \in C_{\mathrm{jk}} \\ 0, & \text{otherwise} \end{cases}.$$

The count

$$n_{\mathrm{kj}} = \sum_{i=1}^{n} I_k(i,j)$$

is the number of votels inside consensus region j of voting image k. Breaking ties arbitrarily, let C_k^*, the ensemble consensus region, be any C_{jk} with max n_{kj}.

A consensus region can be projected onto a line in the voting image plane to obtain a consensus *interval*. Table 1 summarizes votel analysis for the votels shown in Fig. 11, where consensus regions are projected onto the x axis to obtain three consensus intervals. Consensus interval three, with the most votels, is the ensemble consensus interval.

C. Leadership Metric

One way to score individual performance is to define a measure of "leadership." By definition, a "leader" is an individual who is followed by the group. In collaborative teleoperation, a leader is an individual who anticipates the consensus, by voting early in a position that corresponds to what emerges later as the ensemble consensus region. We can formalize this based on a moving average of votel arrival times and ensemble consensus regions as follows.

Let

$$L_{k+1,i}(l) = \frac{1}{l} \sum_{s=k-l}^{k} \left(\frac{T_s - t_{s,i}}{T_s} I_{s,i} \right)$$

where $L_{k,i}(l)$ is the leadership metric of voter i for k^{th} voting image, $t_{s,i}$ is the voter i's votel arrival time for the s^{th} voting image, T_s is the total voting time for voting image s, and I_s is an outcome index

$$I_{s,i} = \begin{cases} 1, & \text{if } [x_{i,s}(T_s), y_{i,s}(T_s)] \in C_s^* \\ 0, & \text{otherwise} \end{cases}.$$

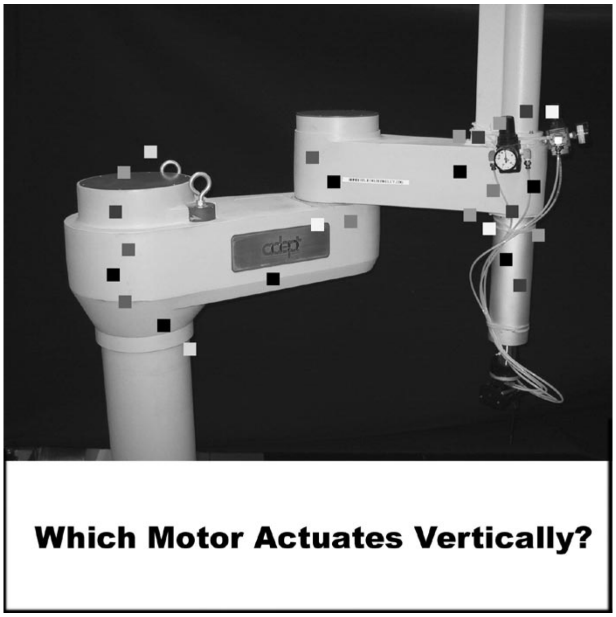

Fig. 11. Voting image of an industrial robot arm with 27 votels.

Recall that C_s^* is the consensus region of voting image s and $[x_{i,s}(T_s), y_{i,s}(T_s)]$ is the position of voter i's votel at time T_s; $L_k(l)$ is the moving average of l random variables $(T_s - t_{s,i}/T_s) I_{s,i}$. If we assume that each voting image is independent, and that the variables are identically distributed, $L_{k,i}(l)$ will converge to its true mean as the l and k increases. We can determine a confidence interval using the central limit theorem for a finite l. It is important to choose a finite l because each voting image is not independent.

Leadership can also be computed incrementally

$$L_{k+1,i}(n) = \frac{1}{l} \left(L_{k-1}(l) \cdot l - \frac{T_{k-1-l} - t_{k-1-l,i}}{T_{k-1-l}} I_{k-1-l,i} + \frac{T_k - t_{k,i}}{T_k} I_{k,i} \right)$$

Fig. 12 illustrates the leadership measure for four participants as it evolves over a series of voting images.

D. Collaboration Metric

To what degree are voters collaborating? We define a measure of collaboration based on the density of votels in each consensus region. For consensus region j in voting image k, define the votel density ratio as

$$D_{\mathrm{kj}} = \frac{d_{\mathrm{kj}}}{d_k} = \frac{\frac{n_{\mathrm{kj}}}{a_{\mathrm{kj}}}}{\frac{N_k}{A}} = \frac{n_{\mathrm{kj}}}{N_k} \left(\frac{A}{a_{\mathrm{kj}}} \right)$$

where d_{kj} is the votel density (votes per unit area) for consensus region j, d_k is the overall average votel density for the voting image k, n_{kj} is number of votels in consensus region j, a_{kj} is the area or width of the consensus region j, N_k

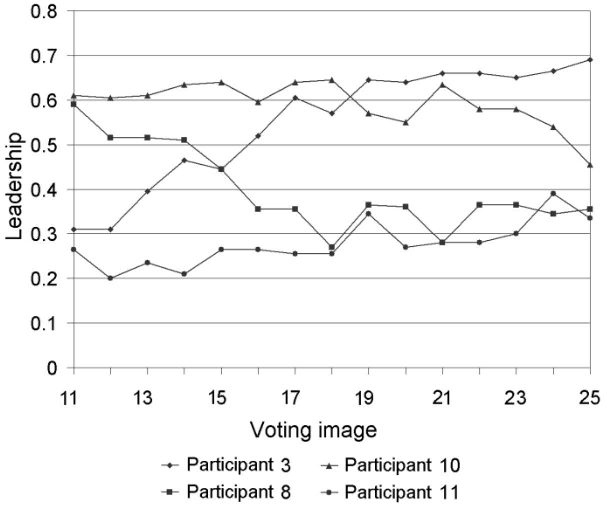

Fig. 12. Moving average of the leadership measure for four participants over 14 voting cycles.

Table 2
SDV Analysis for Another Voting Image

C_{jk}	Interval	Width	#Votes	D_{kj}
1	[44, 84]	40	10	2.35
2	[141, 168]	27	6	3.32
3	[223, 283]	60	16	2.51
Overall	–	127	32	2.37

is the total number of votes, and A is the area of the voting image. This metric is proportional to the ratio n_{kj}/N_k and inversely proportional to the area of the consensus region. The metric is high when many votes are concentrated in a small consensus region and low when votes are uniformly spread among multiple consensus regions. We can also compute an overall collaboration level for voting image k

$$D_k = \frac{\sum n_{\mathrm{kj}}}{\sum a_{\mathrm{kj}}} \frac{A}{N_k} = \frac{A}{\sum a_{\mathrm{kj}}}$$

which can measure how focused the votels are.

Table 2 gives results for another voting image. The collaboration measure for each consensus region is given in the last column of Tables 1 and 2. In Table 2, the data suggests that users are collaborating in a focused manner to vote for consensus interval two even though it has fewer votes than consensus interval three.

VII. FUTURE WORK

This paper describes a networked teleoperation system that allows groups of participants to collaboratively explore remote environments. We propose two innovations: the SDV, a networked interface for collecting spatial inputs from many simulataneous users, and the “tele-actor,” a skilled human with cameras and microphones who navigates and performs actions in the remote environment based on this input. We presented problem formulation, system architecture and interface, and algorithms for processing voting data.

Collaborative teleoperation systems will benefit from advances in broadband Internet, local wireless digital standards (802.11x), video teleconferencing standards, and gigahertz processing capabilities at both client and server. We are working on efficient algorithms for consensus identification and “scoring” to motivate user interaction. We will perform a series of field tests with different user groups and different remote environments.

In related research, we are developing collaborative teleoperation systems where the shared resource is a machine such as a robotic pan-tilt-zoom camera. Our goal is systems that are viable for very large groups (1000 person and up), allowing collective exploration over networks such as Internet2 and interactive television.

The latest version of our system can be found at http://www.tele-actor.net.

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