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ABSTRACT

This paper presents a summary of a new remote tokamak control room constructed near the offices of DIII-D's scientific staff. This integrated system combines hardware, software, data, and control of the room (R-232) into a unified package that has been designed and constructed in a generic fashion so that it can be used with any tokamak operating worldwide. The room is approximately 300 ft^2 and can accommodate up to 12 seated participants. Mounted on the wall facing each scientist are five 52" LCD televisions and mounted to the wall on their right are six 24" LCD monitors. Each seat has associated with it a 24" monitor, network connection, and power and the scientist is either provided with a computer or they can use their own. The room has been used for operation of DIII-D, EAST, and KSTAR. Due to the long distances, data from EAST and KSTAR was brought back to local DIII-D computers in one large parallel network transfer and subsequently served to scientists in the remote control room to other US collaborators. This parallel data transfer allowed the data to be available to US participants between pulses making remote experimental participation highly effective.

1. INTRODUCTION

The scientific staff that participates in planning and conducting experiments at the DIII-D National Fusion Facility and analyzing data and presenting the results is comprised of 500 researchers from 100 institutions world wide including 55 U.S. national laboratories, universities, and industry, and 45 international universities and laboratories. Of this staff only approximately 20% are collocated with the experimental facility. This personnel mixture has led to significant collaborations between the DIII-D facility and other magnetic fusion facilities worldwide.

This collaborative mindset was certainly fostered under the auspices of the Doublet III program, the predecessor to DIII-D that was operated under a U.S./Japan cooperation (DOE-JAERI) program [1]. This highly beneficial collaboration between the DOE and JAERI continues to the present day. Given that success, it became natural to implement similar cooperative programs and the expanded magnetic fusion research programs of China and South Korea presented another opportunity as these countries designed and built new superconducting experimental magnetic fusion devices (EAST and KSTAR). For the DIII-D program specifically, this afforded the opportunity to transition the DIII-D Plasma Control System, including a robust simulation capability to a superconducting environment and to work in conjunction with other international operation and control experts during the start-up phase for these devices [2]. Since DIII-D personnel were supporting DIII-D operations as well as EAST and KSTAR, travel time to their Asian counterparts was limited. In this type of environment remote collaboration tools increase in importance.

It was within this environment that the decision was made to build on previous remote control room work [3] and construct a new dedicated remote control room that could not only support the remote operation of EAST and KSTAR but also be used by DIII-D scientists whose offices are several kilometers away from the experimental facility. Since available space was limited (~300 ft^2), there was no opportunity to optimize the control room design and therefore the results presented are not intended to represent a full room ergonomic study. Instead, given the square-shaped room and approximately 10 ft ceiling height, this study represents an examination of what hardware/software combinations can be used to enhance collaboration in a dedicated remote control room.

In this paper, we examine remote collaborations that consist of many scientists and also have an element of control associated with them rather than just remote participation. Note, that this differs from remote collaborations that are one to one or one to many. Section 2 presents the users' requirements as well as the limitations presented by the available physical space. In Section 3, the remote control room design is presented and Section 4 details the specific applications that needed to be created. Finally, Section 5 discusses the results of initial usage and the plans for future work.

2. REQUIREMENTS AND LIMITATIONS

The basic room requirement was to support startup and operation of a new tokamak. Therefore, this room was to go beyond the normal remote collaboration associated with participating in the experimental physics element of tokamak operations but was also to include elements of startup and plasma operation including plasma control. Therefore, the room needed to be able to support a variety of users with different interests.

Additionally, there was a desire to study remote operation and control with a larger group of scientists. With an eye towards ITER, there was a requirement to understand how larger remote control rooms might be designed with the realization that lessons learned could be folded into not only remote rooms for ITER but for the actual ITER control room itself.

Given these higher level requirements, the specific requirements can be summarized as: 1) supporting ~10 individuals simultaneously, 2) real-time human communication with the remote experimental facility, and 3) allowing sufficient analysis of experimental and control data to permit suggestions to be made to the on-site experimental team in the time frame of the between pulse cycle. The last requirement implies that the scientists in the remote control room have access to the same information on the same time scale as the on-site personnel. If this information is delayed beyond the between pulse cycle time, it is impossible for the scientists in the remote control room to contribute to decisions affecting the next pulse. Therefore, the last requirement was broken down into two distinct pieces. First, the experimental and control data needs to be rapidly available for analysis and visualization applications that are being used by the scientists in the remote control room. Second, visualizations that are commonly displayed automatically on-site, after every pulse, need to be reproduced in the remote control room.

The fundamental limitation of this study was in the choice of room locations. The ability to construct a new building was not an option so the task became one of finding an existing space that could be repurposed. In the end, half of the existing room that was previously used for remote control room studies [3] was identified to provide a space that was approximately 20' deep and 16' wide with a 10' ceiling. It is the space on the left hand side of Fig. 1 from reference [3] that was repurposed for this study. There was no ability to raise the ceiling so the height at which any general room displays could be placed was limited. It is for these physical room limitations that this study does not represent a full-room ergonomic study.

After some initial examination and striping the room bar of all equipment, it was determined that this room could accommodate 12 seated participants (Fig. 1). In order to reduce the cost of completely outfitting the room, it was also decided to create these seated areas without computers and require the scientist to bring in their own laptop. A large number of the scientists located at DIII-D have their own laptops so this limitation was not too onerous a burden on their usage of the room. Furthermore, it did not restrict the room design or deployment. In the future, it would be simple to add a dedicated computer system in a larger dedicated room.

Fig. 1. Remote control room schematic from overhead showing 12 seats available scientific staff. The left side shows 5 TVs and the top shows six 24” LCD monitors.

3. DESIGN

Based on the requirements and limitations outlined in the previous section a room design was created that can be broken down into displays, screen sharing, room control, and data transfer.

3.1 DISPLAYS

In an on-site control room, the remote control room allows numerous scientists to collaborate amongst themselves. To facilitate this type of interaction, large centrally mounted displays figured prominently in the design. Borrowing on ideas successfully deployed in the DIII-D control room [4], larger displays were used for more experiment-centric quantities of interest that can change daily and smaller displays for signals associated with machine control and operation required for all experiments.

The physical dimensions of the room allowed five 52” LCD TVs to be mounted on the wall facing the scientists (Fig. 2). Four of these TVs are stacked in two rows of two and one TV is rotated 90° and placed adjacent to the stack of four. Given the elongated nature of modern tokamak design, the rotated TV with its 1.78 ratio of height to width is well suited for display of real-time plasma boundary calculation where DIII-D’s machine elongation is ~1.8. Each TV is connected to an Apple Mac mini running OS X. Applications can be run either natively on these machines or alternatively X Windows can be used allowing programs to be run on a different computer.

Fig. 2. The remote control room as used during KSTAR operations. Five large TVs face the scientific staff and 6 smaller 24” monitors display plasma control quantities (right).

Mounted to the right of the scientists are six 24" LCD monitors mounted in two rows of three each. These screens are used to display data associated with the plasma control system including raw diagnostic data and computed quantities. These six screens are controlled via three Mac mini computers (two displays per computer). Each screen is divided into four quadrants with each one displaying a temporal history of two quantities resulting in a total of 48 traces.

3.2 SCREEN SHARING

There are a total of 12 seats in the room for participants. Each participant has a 24" LCD monitor with display cable, an Ethernet network cable, a mouse and keyboard, and a power outlet. Scientists are expected to bring their laptop computer and either run applications natively on the laptop or use X Windows to log onto one of DIII-D's generally available Linux workstations.

The requirement to facilitate collaboration amongst the group necessitated the ability for scientists to be able to place the content of their local display on one of the large TVs. Previously, this functionality was accomplished in the DIII-D control room via a specialized application. However, to simplify the design and usage of this room, it was decided to perform this function via hardware. Therefore, each TV can be RS-232 controlled so that via the general room control, it is easy for a scientist to switch one TV input to show their own screen.

This type of screen sharing placed additional hardware requirements on the final design. First, to simplify the physical deployment of cabling (both bulk and length), the DVI signal from each seat was converted to run over shielded twisted pair (CAT 6 cable) using a transmitter/receiver hardware set per display. Second, to allow usage of any of the four TVs by any of the scientists, a DVI Matrix switch was deployed. Finally, a DVI emulator was required to transmit a constant Extended Display Identification Data (EDID) signal allowing routine switching from the desktop display to the TV display. The EDID emulator captures and retains EDID information from the display ensuring an optimum signal is provided to the display, regardless of whether or not there is a direct connection between the source and the display.

3.3 ROOM CONTROL

Allowing variability in display usage required the ability to have a simplified control scheme so that the burden of room usage and setup was not placed on the scientific staff. One way to simplify room control layout was to allow control of the five large displays via a customized application that communicates via Ethernet. Therefore, a serial-TCP/IP (RS-232 - Ethernet) convertor was installed where one Ethernet input port allows RS-232 connections to all five large displays.

A Linux workstation was installed in the remote control room to run the room control application (see Section 4). This computer was connected to a Gigabit switch that created a dedicated local area network for the remote control room that included the Apple Mac mini computers and the scientists' laptops.

3.4 DATA TRANSFER

All displays and easy room control are rendered meaningless if the availability of the experimental data is delayed so that its examination before the next plasma pulse is precluded. For usage of the remote control room for DIII-D operation, the local area network to the main DIII-D data repository is fast enough that the tools that work in the DIII-D control room are sufficient for the remote control room. One exception is needed for the real-time data display. In the DIII-D control room, the real time displays of plasma boundary and PCS-related data is accomplished via shared memory techniques. For the remote control room, the data (~ 50 MB) local to the DIII-D control room that is in shared memory is dumped from memory to a file, the file is then transferred to a local computer in the remote control room, and then the file contents moved to computer RAM where the real-time scope application can perform visualization. This results in a delay of approximately 15 s.

However, DIII-D's client-server data retrieval design where individual signals are requested, retrieved, and then plotted together breaks down when data requests are made over long distances to our collaborating partners in EAST and KSTAR. To overcome this problem, a design was created where the entire remote data repository for a given plasma pulse was bundled into one file and transmitted via parallel network streams to a dedicated computer on the DIII-D internal network. Scientists in the remote control room could then use their traditional client-server tools to access data from this local data repository for analysis and visualization. Details on this application are in the next section.

4. APPLICATIONS

Applications used in the remote control room are comprised of those that were previously used at the DIII-D facility and those created specifically for the new room.

4.1 ROOM CONTROL

There are multiple hardware devices and dedicated software applications in the remote control room. The hardware devices were not originally built for seamless integration as required for the remote control room. Each hardware device has its own control interface. For example, the TVs share the same remote control resulting in no easy way to independently change their inputs or resolutions. Furthermore, since this room is designed for remote participation to different experimental facilities, room setup including applications and data sources need to be set up differently for different tokamaks. Therefore, an efficient and centralized room control mechanism was needed.

A web-based control application was developed for centralized control of the room. On the front end, users interact with the web interface to control multiple hardware components including turning devices off and on, changing input of the TVs, and controlling video conferencing equipment. The same interface also provides access for configuring applications and data sources for different tokamaks. This user interface design is compatible with both desktop and mobile devices. On the back end, the web server triggers multiple applications to communicate with hardware devices and computers via TCP/IP sockets and serial communication ports. The web server runs on a dedicated computer in the remote control room that runs Linux OS and an Apache web server. Figure 3 shows the architecture of web-based control application and Fig. 4 shows a snapshot of the TV control interface.

4.2 DATA MANAGEMENT AND TRANSFER

Since the success of remote experiment participation relies on remote collaborators having fast and efficient access to the experiment's data signals, a number of technologies were used enable efficient data handling.

MDSplus data management servers were already in use at DIII-D, EAST, and KSTAR. Therefore, it was natural to use MDSplus events to notify when particular data files were available to be transferred between pulses. Using event-driven scripts during the experimental cycle, it was possible to automatically retrieve data files and begin data transfer to the remote site immediately after the data was written. This automation ensures that no time is wasted initiating the data transfer (Fig. 5).

Copying individual pieces of data from either EAST or KSTAR back to the DIII-D facility was inefficient over the long-distance network. Gathering the data into one large file and making a simple transfer was too cumbersome. For example, moving one data file from EAST to the DIII-D facility took ~5 to 10 minutes — much too slow for the experimental pulse cycle.

Therefore, techniques to transfer the data using multiple, simultaneous TCP/IP streams were deployed. This technique involves better usage of available bandwidth.

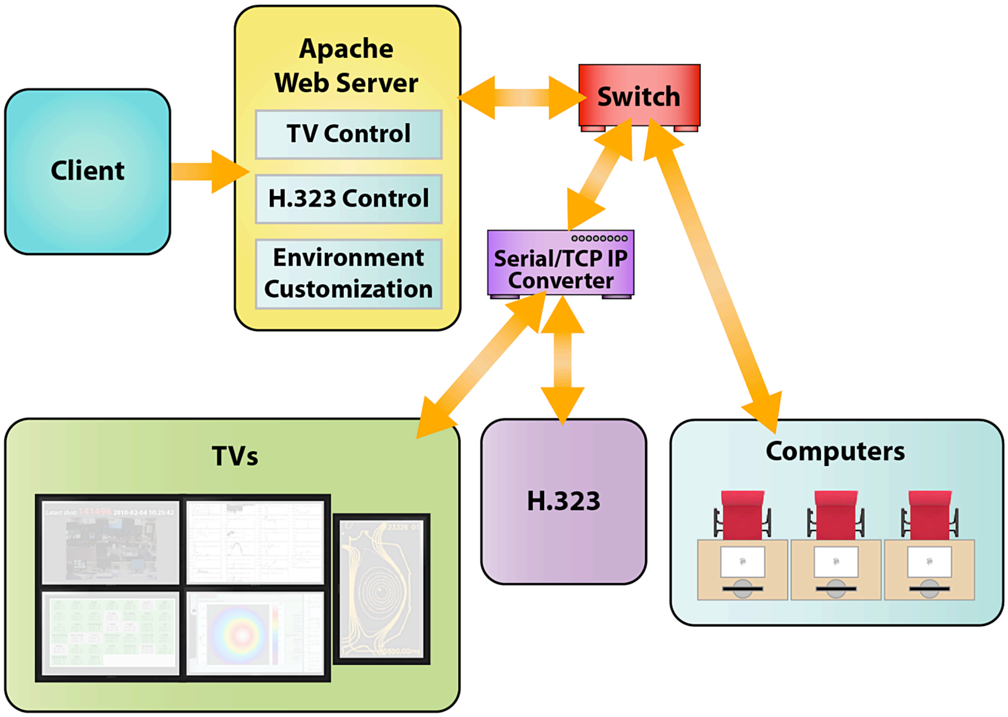

Fig. 3. Room control is accomplished via RS-232, Ethernet, and a web server that presents web pages to the scientist for simple one button control.

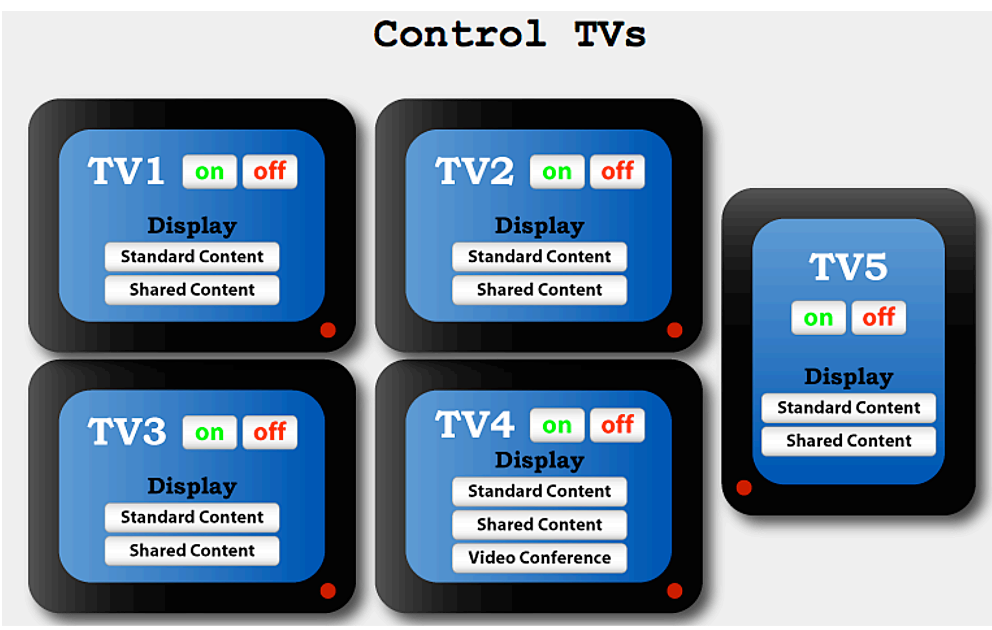

Fig. 4. The web page presented to the scientist allowing simple web browser based control.

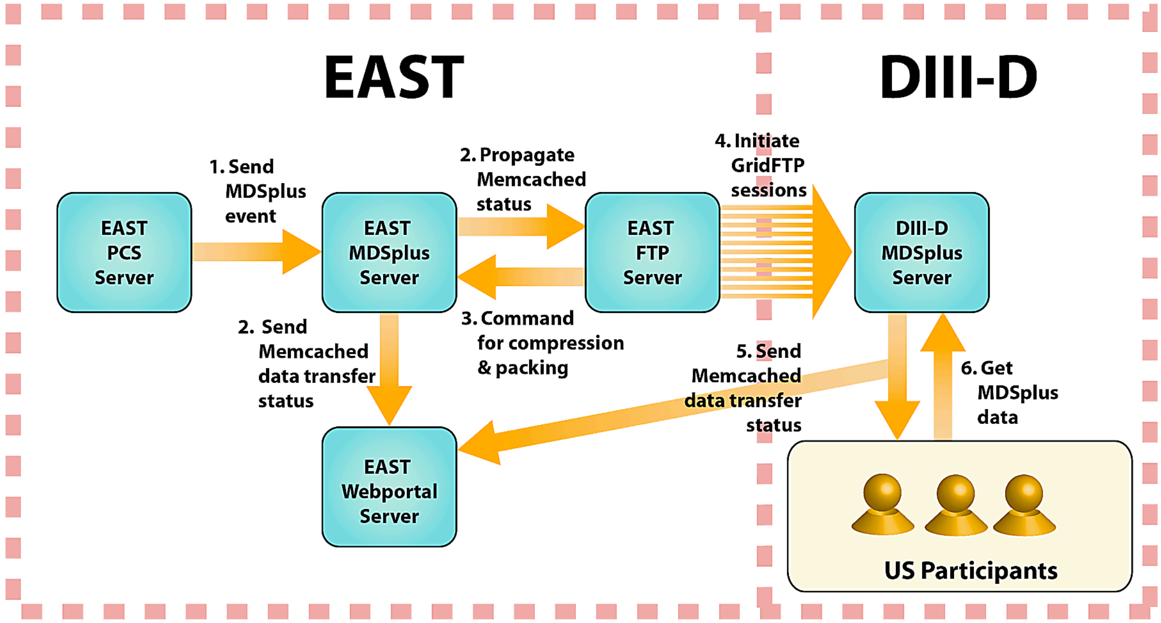

Fig. 5. The layout for parallel data transfer between EAST and DIII-D utilizing both MDSplus and GridFTP technologies.

To utilize this parallel IO technique, all relevant MDSplus files were gathered together and tarred into one compressed file for long-distance transport. Both GridFTP [5] and FDT [6] were used for long-distance parallel network transport. Utilizing these techniques, the 5-10 minute transfer time could be reduced to less than 1 minute. When this single compressed file arrives at the DIII-D facility, it is unpacked, and placed in an MDSplus server that is available to authorized scientists in the remote control room.

A mechanism was also created to keep staff in the remote control room informed of data transfer status. Memcached [7] is a distributed memory caching system used to report the status of data transfer between the experiment facility and the remote control room. The WebPortal discussed in the following section uses Memcached to keep track of the status of data transfer so that remote collaborators know when data has been transferred to the local MDSplus data server and is ready to be retrieved for analysis.

4.3 FUSION SCIENCE APPLICATIONS

Although it is possible to utilize existing fusion-specific applications designed for desktop use on the remote control room large display screens, in practice this is not the best utilization for these large displays. First, desktop applications have menus, check boxes, drop down lists, all designed for mouse interaction by the user. However, applications running on the large display screen are not intended to be interactive and thus the pixels used to display user interaction areas are wasted. Second, the size and colors of characters, symbols, and lines are designed for viewing from a relatively short distance. This is in contrast to the remote control room where the displays, although larger, are considerably farther away from the typical desktop screen.

To deal with these issues, existing web applications were customized for large displays via the cascading style sheet (CSS). Character sizes were increased, fonts changed, and colors modified to yield the best visibility to the room's audience. Additionally, utilizing a web browser (Firefox) that has a full-screen view eliminated the unwanted menu bar from the top of the screen. These modified web-based applications included scientific graphics for display of data traces that are critical to each experiment. Items that are typically displayed on the large screens are the logbook comments, the shot clock, experimental status, data analysis monitor status, general information on the experiment, and various signal plots.

The one rotated screen is dedicated to the real-time plasma shape display. This application is the same as that used in the DIII-D control room. The six small displays on the side of the room are used for signals associated with the plasma control system. These signals include commands as well as systems response and are critical for rapidly diagnosing any issues associated with plasma control. The application that displays these signals is also identical to that used in the DIII-D control room.

5. DISCUSSION

Initial usage of the remote control room have occurred with DIII-D, EAST, and KSTAR operation. Since the room is relatively new, it is too early for extensive feedback on its design and implementation. However, some initial observations can be made.

Most important for this entire activity is timely access to the data. The technique described in this paper utilizes parallel network streams to overcome the latency issues associated with long distance networks. However, another method is desktop virtualization where compression and session resilience techniques make it possible to run a graphical application over the wide area network. In this situation, the scientist in the remote room uses desktop virtualization to log into computers collocated with the experiment and run applications native to the experiment. As long as running the graphical application is fast enough, the advantage is the rapid availability of data. Although this technique is showing promise for desktop applications, its applicability to the large displays is not so clear. Over the next year, these two techniques will be compared in more detail so that a proper evaluation can be performed.

For a room that is being used on multiple tokamaks, the ability to rapidly switch from one to the other can be important. For example, in this remote control room it is possible that as support of KSTAR concludes the support of DIII-D begins with a different team. Therefore, the ability to completely change the content of the large displays, to utilize new data servers, and to display plasma control data from a different source on a relatively rapid time scale is important. As experience is gained with the remote control room, techniques will be investigated to allow a simple change over as opposed to today where a specialist must be present to reconfigure everything to support a new experiment.

One advantage of the remote control room is that it allows the ability to experiment with new display content outside of the high-pressure arena of the main control room. Testing different fonts, character sizes, colors, and different content layout patterns are not typically welcome in the operating control room since they interfere with scientific operation. Utilizing the room as a proving ground for new control room tools should result in the creation of better tools that can be transitioned into the main control room.

Looking towards the future, this remote control room should be an excellent proving ground for techniques associated with future collaboration with ITER. The requirements today are very similar to what will be encountered on ITER by the many domestic agencies. The need for rapid data access will be the same yet the higher volume of data will elevate the challenge. An understanding of how to replicate data, on what time scale, and the role of desktop virtualization need to be analyzed in more detail so that concrete suggestions can be presented for consideration by the ITER organization. The ability for distributed scientists to easily and rapidly discuss results will be critical for successful operation of ITER. The dynamics of communication that are required (e.g. one-to-one, one-to-many) and the sociology associated with there implementation need to be addressed. It seems clear that as the ITER project moves forward, the technologies being developed should be prototyped and tested on the current generation of experiments. To that end, the remote control room described in this paper has begun such prototyping with DIII-D, EAST, and KSTAR.

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