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MACS: A Simulation Platform for Today's and Tomorrow's Air Traffic Operations

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This paper describes the Multi Aircraft Control System (MACS) simulation platform developed in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center. MACS is a comprehensive research tool that has been developed to increase the overall realism and flexibility of controller- and pilot-in-the loop air traffic simulations. The research focus in the AOL is on examining air traffic operations in rich air/ground environments that can include multiple oceanic, en route, and terminal airspace sectors. The AOL research and development team maintains and continuously expands the capabilities of MACS to rapidly prototype new interfaces, displays, tools and operational concepts for addressing the complex controller/pilot/automation integration crucial to the implementation of the Next Generation Air Transportation System (NextGen). Sample applications of the MACS software are presented to show the range of air traffic environments that can be investigated. Funding for this work was provided by NASA's Aeronautics Research Mission Directorate (ARMD) and NGATS Airspace Systems research program.

Nomenclature

AAC	=	Advanced Airspace Concept
ADRS	=	Aeronautical Datalink and Radar Simulator
ADS-B	=	Automatic Dependent Surveillance-Broadcast
AOL	=	Airspace Operations Laboratory
ARTCC	=	Air Route Traffic Control Center
ATC	=	Air Traffic Control
ATM	=	Air Traffic Management
ATOP	=	Advanced Technologies and Oceanic Procedures
CDTI	=	Cockpit Display of Traffic Information
CPC	=	Certified Professional Controller
D-Side	=	Radar Associate Controller
DSR	=	Display System Replacement
DYSIM	=	Dynamic Simulation
FAA	=	Federal Aviation Administration
FMS	=	Flight Management System
JPDO	=	Joint Planning and Development Office
MACS	=	Multi Aircraft Control System
MAP	=	Monitor Alert Parameter
MSP	=	Multi-Sector Planner
NAS	=	National Airspace System
NASA	=	National Aeronautics and Space Administration
NextGen	=	Next Generation Air Transportation System
OJF	=	On-The-Job Familiarization
OJT	=	On-The-Job Training
TRACON	=	Terminal RADAR Approach Control
R-Side	=	Radar Controller
RADAR	=	Radio Detection and Ranging
STARS	=	Standard Terminal Automation Replacement System
ZOA	=	Oakland ARTCC

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I. Introduction

Research in the Airspace Operations Laboratory (AOL)[1] at NASA's Ames Research Center focuses on examining air traffic operations in rich air/ground environments that can include multiple oceanic, en route, and terminal airspace sectors. The AOL has been designed for studying air traffic operations in the current environment, possible NextGen[2] environments, as well as the transitional stages in-between. The Multi Aircraft Control System (MACS)[3] provides the AOL's software environment for rapid prototyping and controller- and pilot-in-the-loop simulations to evaluate air/ground interactions in the National Airspace System (NAS).

Since its first use in an AOL simulation in 2003, MACS has progressed substantially in terms of realism and functionality. Studies conducted in the AOL over the last few years have called for several modifications, updates, and additions to MACS, bringing tremendous growth to its functions and capabilities. Documents generated from the AOL group typically serve to inform the scientific community of the data and results of human-in-the-loop air/ground simulations, but do not always go into the details of the MACS configurations, settings, and features. Rather than discuss the usage of the MACS software in all past simulations, three examples were chosen to give the reader an idea of the range of possibilities capable with MACS. This paper will discuss three recent uses of the MACS software, focusing on the details of the software interface and configuration.

II. The Multi Aircraft Control System (MACS)

MACS is a JAVA program that provides high-fidelity display emulations for air traffic controllers/managers as well as user interfaces and displays for confederate pilots and flight crew participants, airline dispatchers, and experiment managers, analysts, and observers. The same software is used for many different applications. Flight simulators, flight management systems, pseudo pilot systems, air traffic displays and advanced air traffic management tools have many common requirements. At a basic level, all applications need to maintain aircraft state and environment information, have models of aircraft dynamics, and have trajectory generation capabilities. Consequently, all MACS operator stations are instantiations of the same software running in different operator modes. Varying how this information is accessed and presented across the many workstations in a distributed simulation is central to the flexibility of MACS. A separate process, the Aeronautical Datalink and Radar Simulator (ADRS) serves as a communication hub and provides a networking infrastructure that allows for an unlimited number of MACS operator stations to be connected together. MACS also has built-in scenario and target generation capabilities, which are used to generate and run traffic problems tailored to the specified challenges of a research project. An integrated and flexible data collection system is used to collect the quantitative measures of interest at each operator station as well as overall traffic progression, including aircraft states, conflicts, and sector counts.

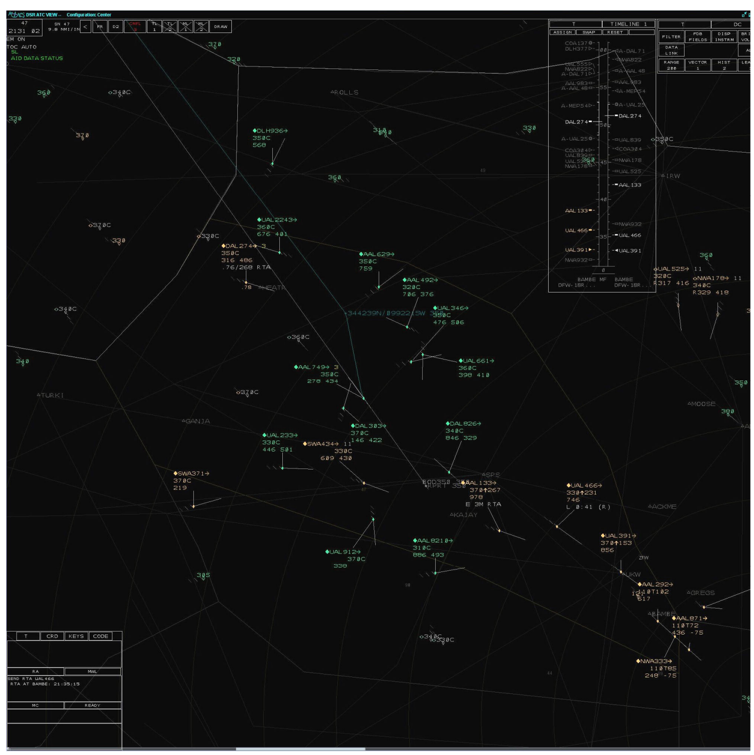

Figure 1. MACS DSR display with advanced capabilities.

One of MACS' strengths is its accurate emulation of current systems. After several years of experience, the AOL has incorporated the critical pieces of a simulation environment that give experts, such as Air Traffic Controllers, the impression of a very realistic situation, not just something slightly better than a video game. Emulating the vital aspects of the fielded controller's display behavior and supporting automation, combined with using the fielded controller keyboard, trackball and monitor to interact with, provide the controller participants with the backdrop for a very real simulation. Further enhancing the simulation environment is the AOL's use of subject matter experts to staff any non-participant controller positions, giving the participants realistic interactions with, for example, the neighboring sector. Currently MACS has air traffic control (ATC) display emulations for the en route (DSR), TRACON (STARS), and oceanic (ATOP) domains. Figure 1 shows an example DSR emulation with advanced capabilities.

Complementing the high-fidelity controller workstations are MACS' flight deck capabilities. Whether combined with a Cockpit Display of Traffic Information (CDTI), or used as a confederate pseudo-pilot, MACS appropriately simulates current-day flight technologies to allow controllers to issue standard and non-standard clearances. To achieve this in a distributed simulation environment, the pilot workstations can be configured to either reflect the look of a modern glass cockpit emphasizing the correctness of the controls, or present generic input devices designed for quickly entering commands for multiple aircraft (see Figure 2). Tying these air and ground sides together is an emulation of current-day communication, navigation and surveillance technologies, which provides the appropriate system response to controller instructions. The level of realism achieved in the AOL helps validate simulation research, useful for comparing current-day "baseline" conditions to those with more advanced concepts.

Testing such advanced concepts highlights another one of the strengths of the MACS software: rapid prototyping. One of the design goals in the AOL is to provide the required functionality to investigate a specific operational concept early in its life cycle. MACS is a research tool only, and it is not intended to be integrated into the operational air traffic system. This relaxes several constraints, while adding significant flexibility to the software. Most existing high fidelity simulation systems are expensive and difficult to modify or extend. Most research prototyping environments are focused on the engineering aspects of new automation but use generic low fidelity operator interfaces. MACS on the other hand, builds on its accurate emulation of current-day systems and provides an infrastructure primed for rapid prototyping. Its object-oriented architecture makes reusing existing components in different ways quite simple, and also allows for the addition of new functions with only minimal programming. A detailed description of MACS and its capabilities was published at the AIAA MST 2006[1].

The remainder of this paper will provide the reader with a record of some recent uses of MACS, describing the software's range of possibilities achievable mostly through end-user configuration settings. The paper will showcase three recent examples of how the same MACS software can be used in very different ways to investigate air traffic concepts ranging from present-day to a near-term future, and on to a far-term, NextGen-like concept.

Figure 2. MACS pilot interface configured to emphasize the correctness of controls found in a glass cockpit (left), and configured for quick entries across multiple aircraft (right).

III. A Current-Day Application for MACS

Over the next decade, the FAA is planning to hire more than 15,000 controllers to address a staffing shortage developing as more and more controllers become eligible for retirement. The entire training process for an en route controller trainee can take more than three years, most of which is spent at the facility doing On-The-Job

Familiarization (OJF), and On-The-Job Training (OJT)[4]. Simulation-based training is used to administer the necessary familiarization, instructional, and evaluation scenarios associated with the trainee's particular facility and area of specialization. Currently, this simulation-based training is done in that facility's Dynamic Simulation (DYSIM) lab. Because of the large number of trainees the facilities will soon have, or in some cases already have, they need a way to train more newly-hired controllers more efficiently.

As part of a FAA and NASA collaboration, the Oakland Air Route Traffic Control Center (ZOA ARTCC) is currently evaluating whether MACS can help in operational error prevention and some part-task training aspects. In 2006, after being briefed on MACS' DSR emulation, ZOA management proposed a trial installation of a MACS training lab to assess any benefits. Working closely with ZOA controllers and training instructors, the DSR emulation was extensively adapted to the Northern California airspace. This included airspace customization as well as a fine-tuning of DSR functions in MACS. Items focused on for this project were those deemed as 'critical' by ZOA training instructors, with the idea that having a key set of functions in MACS would be complementary to the DYSIM lab. Additionally, certain features already in MACS were welcomed as useful functionality that had previously been unavailable to them.

A. System/Lab Configuration

The configuration selected for the MACS training lab consists of two ATC positions each supported by one pseudo pilot station and one simulation management station. This configuration enables independent operations on both clusters. Both ATC stations are equipped with DSR keyboards, trackballs and Keypad Selection Devices (KSD). Several sectors have been adapted and can be run on either of the two clusters. The simulation managers start the problem and automatically initiate the handoffs to the ATC position and the pseudo pilots.

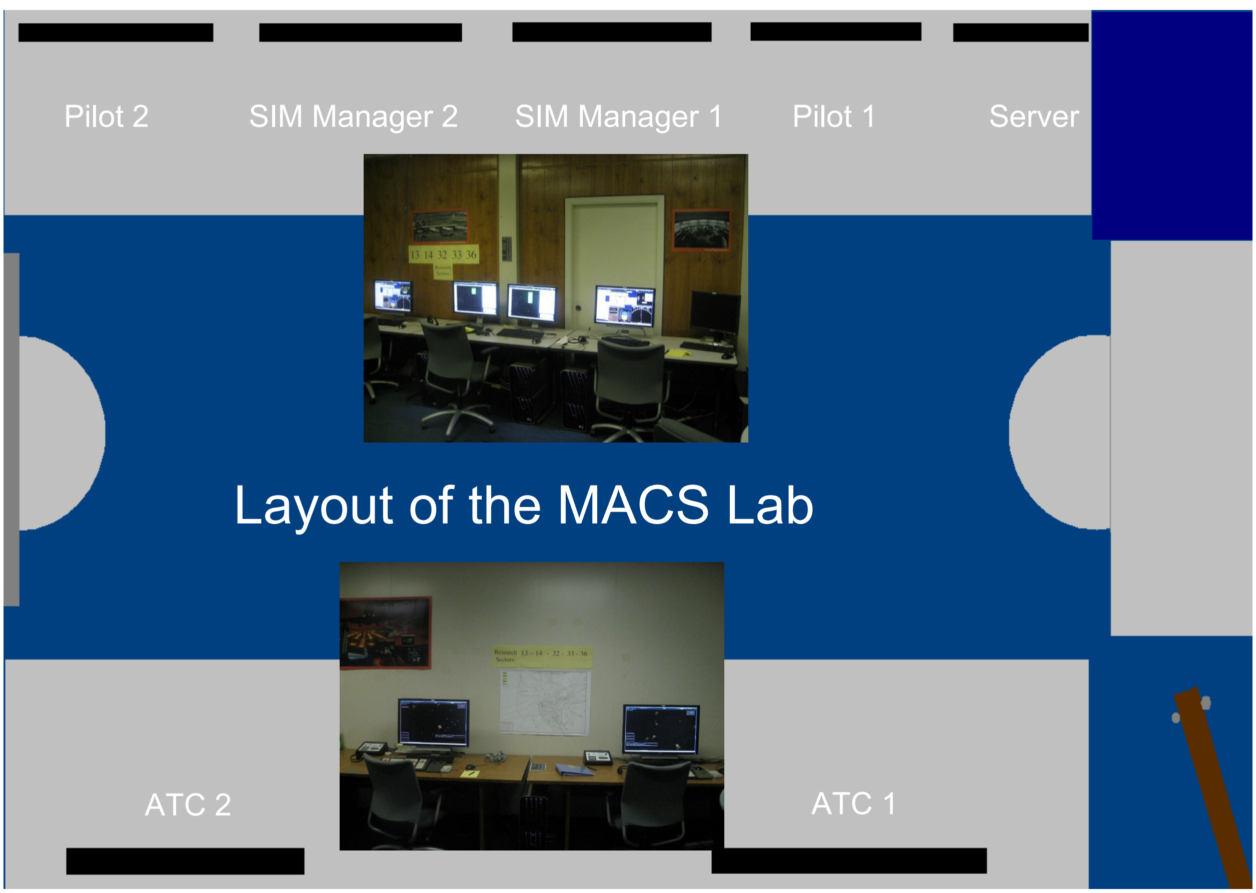

Figure 3: System/Lab configuration for the MACS Training Research Project at Oakland Center.

While the aircraft are within a given sector of interest the controller issues commands and the pseudo pilot controls the aircraft. Upon sector exit, both controller and pseudo pilot can hand the aircraft back to the simulation manager to control the aircraft automatically for the remainder of the session.

B. Airspace elements

As a controller-in-training, learning the spatial characteristics of the airspace is extremely important. By design, MACS is a highly configurable system, allowing numerous possibilities for a display's look and feel. As shown in Figure 4, highly accurate emulations of the actual sector displays were configured for ZOA, providing their trainees with the necessary environmental elements:

1) Sector boundaries were defined to match ZOA's latest configuration
2) Range rings were moved to be centered around a specific waypoint
3) Jet routes and airways were re-drawn to include an 'empty space' of 5nm around intersections
4) The actual radio frequencies for the sectors were integrated into the voice system
5) Particular waypoints were displayed on the sector map, matching ZOA's specifications
6) Display symbols for waypoints were matched to how ZOA differentiates between fixes, airports, waypoints, etc.
7) Charted FMS procedures were updated as any new revisions came out

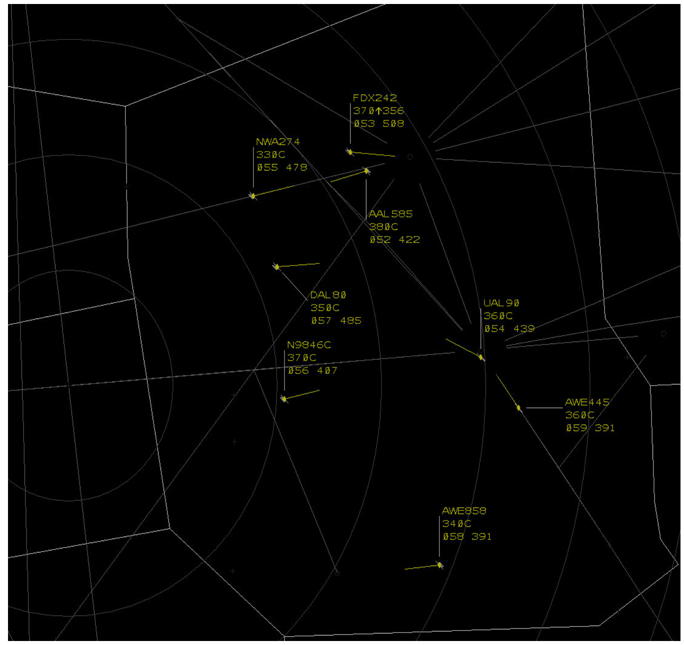

Figure 4. Section of the DSR display for ZOA's sector 33, as configured on the MACS training station.

C. DSR functionality

Having the DSR interface and behavior correct was a crucial piece for this project. It was MACS' initial look and feel that originally got the attention of the ZOA training staff, and working for several months with their instructors and controllers resulted in numerous, although sometimes small, improvements to the fidelity of the DSR emulation. Multiple iterations of incorporating their feedback, accommodating their requests, and sitting down with them while they worked with the latest version, were necessary to get the adequate level of detail for this application (see Figure 5). Seemingly small details from a researcher's perspective were highly scrutinized and focused on by the ZOA staff. Some of the changes were accomplished by simply turning off some of MACS' advanced capabilities, but some did require updates to the software:

1) Dragging of data blocks needed to be turned off

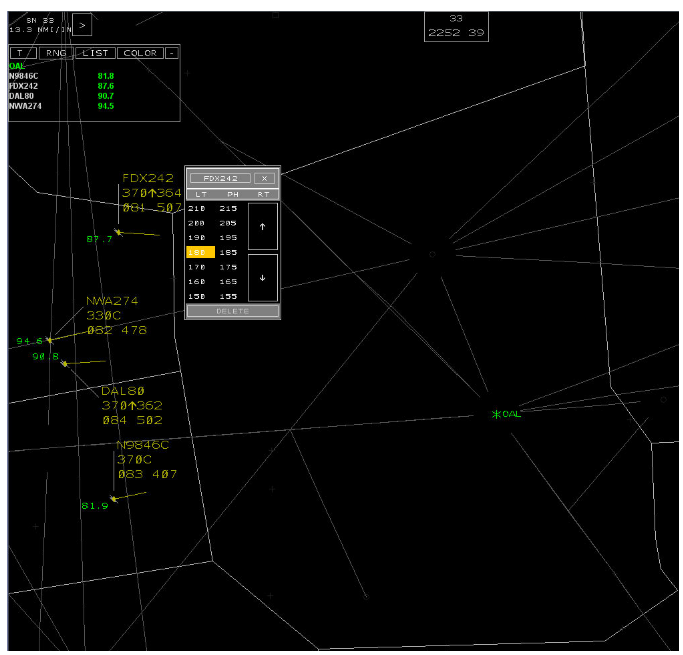

Figure 5. DSR emulation showing fly-out menus and the Continuous Range Readout display.

2) Leader line lengths needed to be adjusted according to ZOA's specifications
3) Leader line attach point needed to be moved to the outside edge of the data block rather than the data block's center
4) Fly-out menus for the 4th line assignments needed a small interface modification
5) The Continuous Range Readout tool needed to be implemented
6) Use of similar hardware- DSR keyboard and trackball, as well as large-format display

D. Relationship to the DYSIM

The DYSIM lab at ZOA has been used successfully for training new hires for several years, and MACS is not intended to replace any part of the DYSIM training. The emphasis of the MACS training research project is on certain tasks that the DYSIM does not do, or does differently.

MACS has the potential to provide some new functionality, like rapid scenario generation to replicate operational error scenarios, or provide a first look at new airspace configurations, most of which is done through adaptation, configurations and settings panels. Having the ability to include interactions between multiple sectors can offer the environment needed to teach handoffs, point-outs, etc. It also promotes more traffic awareness for the student, allowing them to see how the traffic they delivered played out in an adjacent sector.

An air traffic controller also needs to manage aircraft of varying performance characteristics, and under varying weather conditions. MACS maintains a large database of performance characteristics for different aircraft types. These performance tables are usually left alone, allowing the aircraft to perform anywhere within its published limits. Some of the feedback from the staff at ZOA was incorporated into MACS to emulate more realistic aircraft behavior. For example, the climb profiles of a Boeing 757 in MACS was technically accurate, but realistically too aggressive. Tuning that aspect of the performance database helped to present the controllers with traffic scenarios closer to what they see in the real-world. MACS can also be configured with different winds to allow another dimension of variety and realism to its traffic scenarios.

IV. A More Advanced MACS Configuration: Investigating Multi Sector Planning

In a joint study between NASA, the FAA, and San Jose State University, a simulation of a Multi Sector Planner (MSP) concept investigated different air traffic control team organizations, as compared to the current-day radar controller (R-side) and radar associate controller (D-side) team[5]. This study used a suite of ground-side controller tools integrated into MACS for strategic management of air traffic within individual sectors as well as across multiple sectors.

The AOL implementation of this workstation is similar to a controller position zoomed out to view multiple sectors with different rules driving the aircraft data blocks and many automated functions to support the simulation. New functions to support multi sector planner operations include ground-to-ground datalink for coordination of trajectory changes, and interactive traffic load tables and graphs to predict sector loads. The integrated suite of tools in MACS also included lateral and altitude trial-planning integrated with datalink, trajectory-based conflict probing, and datalink for automated transfers of communication,. Using the many MACS configuration options multi sector planner positions have been configured for two objectives; a Multi-D position, which functions as a radar associate controller to three sectors simultaneously, and an Area Flow position, which functions as a localized flow management controller, balancing the sector loads within the three sectors.

A. System/Lab Configuration

The lab configuration used for the Multi sector Planner study represents a typical configuration for conducting ATC-focused human-in-the-loop research in the AOL. Several adjacent sectors were staffed by participant controllers, the surrounding airspace by confederate controllers. Opposite each controller, one or two pseudo pilots managed the voice communications and data inputs required to control the aircraft within the sector. Figure 6 depicts the lab layout of the MSP research configuration. In this case all operator stations were connected and participated in the same simulation.

Figure 7 shows the communication infrastructure underlying this simulation, which involves several instances of the two processes, MACS and ADRS.

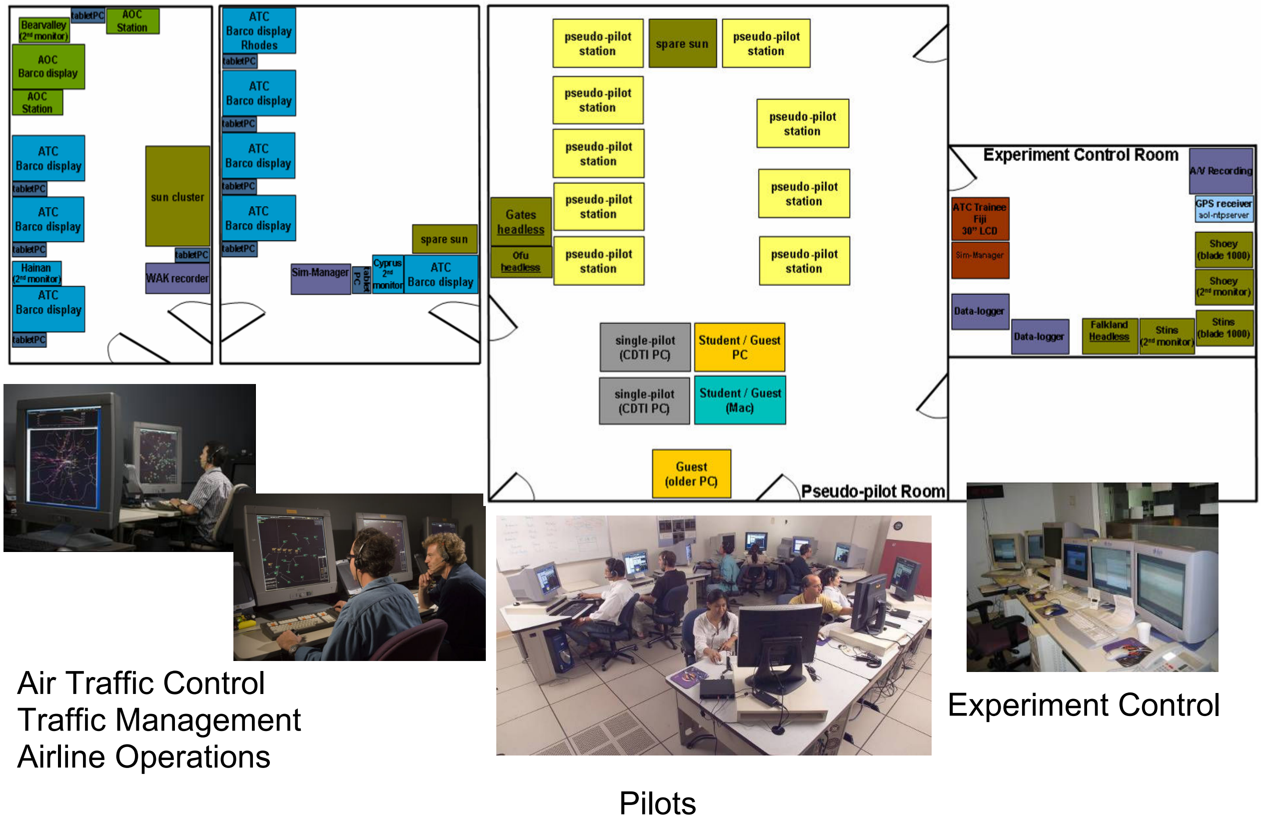

Figure 6. Lab configuration for full mission ATC studies in the AOL.

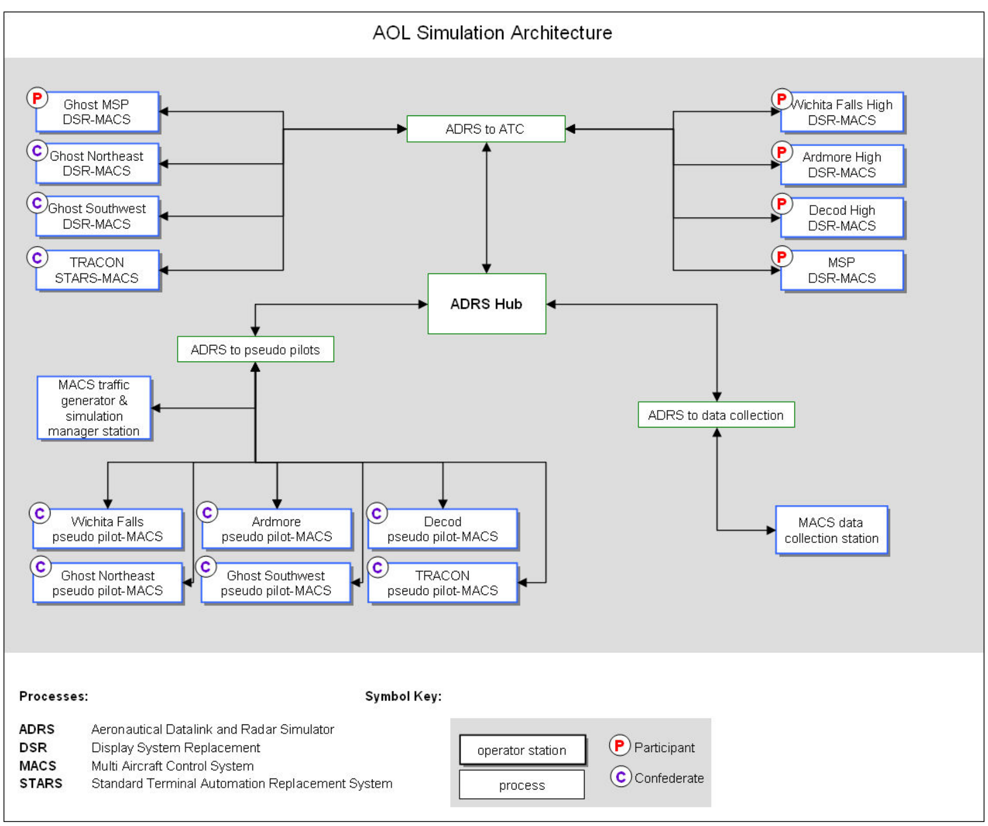

Figure 7. Communication infrastructure for the Multi Sector Planning study.

B. Multi-D workstation

In current-day operations, each R-side working a busy sector is accompanied by a D-side. However in the Multi-D concept, there is a single D-side supporting multiple R-sides. The position provides the capability to perform flight data entries, accept and initiate handoffs, and datalink trajectory changes to the sector controllers and/or the aircraft. The main purpose of this position is medium term conflict detection and resolution to reduce the sector complexity for the R-Side. Shown in Figure 8, the automation at the Multi-D position was designed to provide additional situation awareness about sector complexities and conflicts, and tools to easily generate and communicate trajectory changes. The prototyped tools included the following:

1) Trajectory-based conflict probing that continuously monitors all aircraft for potential conflicts across the MSP's entire area
2) Trial-planning of routes and altitudes integrated with datalink to create modified trajectories that will load directly into a cockpit's Flight Management System (FMS)
3) Datalink-enabled ground-to-ground coordination of trajectory changes. The tool would "forward" a modified trajectory from the Multi-D's workstation to the appropriate R-side for their review and ultimate issuance.
4) "See-all" repeater of the R-side displays used to determine whether the radar controller is already working on a resolution

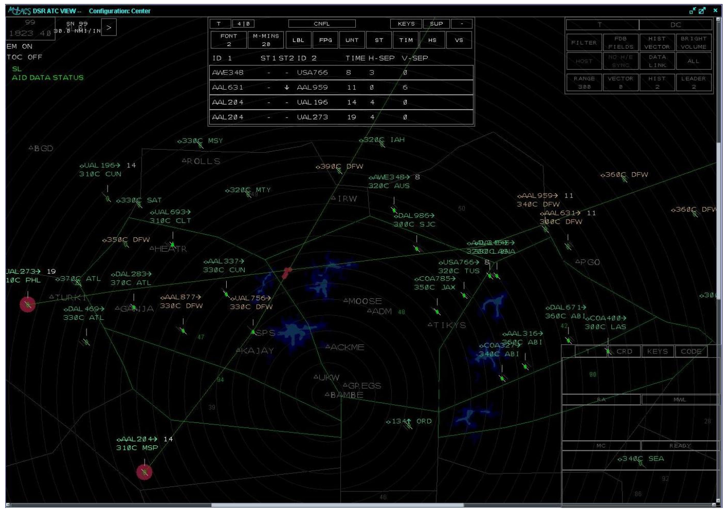

Figure 8. Multi-D display with conflict and weather depiction.

C. Area Flow workstation

A different variation of the MSP concept was an Area Flow controller, which focused on strategic traffic flow management with the goal of reducing traffic load and complexity. The task description specified that the Area Flow controller was not responsible for assisting the R-side controllers with solving conflicts. Instead, the duties of this position included the coordination and implementation of traffic initiatives, flow restrictions, and route changes, handling requests from neighboring Area Flow controllers, as well as planning traffic initiatives in response to off-nominal situations. Primarily though, the Area Flow controller's main task was balancing traffic load levels within their area of responsibility, such that none of the sectors exceed the Monitor Alert Parameter (MAP) value for

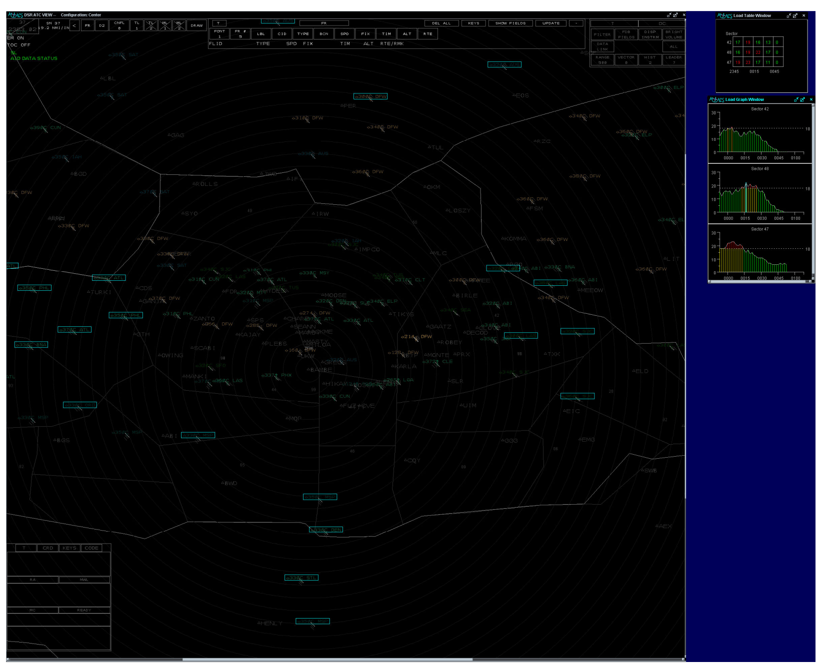

Figure 9. Area Flow display with interactive load graphs and load tables. Here the MSP is displaying those aircraft that will cause sector 48 to go above the specified MAP value.

that sector. Figure 9 shows the supporting toolset for the Area Flow controller, which helped the MSP to analyze the sector loads and make the necessary changes to assist the R-side controllers:

1) Trajectory-based conflict probing that was only turned on for trial-plans, as opposed to for all aircraft. This configuration helped the Area Flow controller make the changes necessary to balance sector loads, while ensuring that they were not producing more conflicts for the R-sides.
2) Rule-based color coding of data blocks that would allow the Area Flow controller to distinguish flights by destination airport, altitude, city pairs, airlines, etc.
3) Interactive load graphs and load tables to help the Area Flow controller assess the sector loads. The prototyped tool predicts the number of aircraft that will be present in the sectors of interest and displays the counts in a table and a graphical format. The indication changes color whenever a predicted load exceeds a pre-set, and user-configurable, value similar to a MAP.

In both MSP configurations, participants were able to use the automation provided to resolve conflicts, avoid convective weather cells, and redistribute anticipated sector loads in challenging air traffic environments. The prototyped tools proved adequate for evaluating the MSP concept, and were also perceived as very usable and useful by the Certified Professional Controller (CPC) participants in the study.

V. NextGen Research: Part-task Study on Machine-based Separation Assurance

Within NASA's current primary research thread on the Next Generation Air Transportation System (NextGen), AOL researchers are involved in investigating machine-based separation assurance concepts. A current part-task study examines ground side aspects of automated conflict detection and automation-supported conflict resolution. Therefore a conflict resolution algorithm was integrated into MACS that was developed as part of the research on the Advanced Airspace Concept (AAC)[6]. This algorithm had been prototyped in JAVA and could therefore seamlessly be integrated into MACS. The first set of human-in-the-loop simulations was just completed in August of 2007 and the data is currently being analyzed. To aid in the analysis, data collection software from the AAC development was also integrated into MACS, enabling a highly efficient web-based collaboration for researchers to assess the progress of the simulation.

The simulated NextGen 2025 environment assumed full ADS-B out and datalink uplink capability for all aircraft. With this assumption, a MACS prototype was created to automatically handle all routine air traffic control tasks, (e.g., handoffs, climb and descent clearances, point-outs, etc.). Furthermore, the improved surveillance and predictability of trajectories enabled the NextGen simulation to focus on conflict resolution strategies in 1, 2, and 3 times current-day traffic densities. The controller stations were re-designed for interacting with a trustworthy conflict probe and automated handling of all routine tasks. The display prototype is described in a subsequent section.

A. System/Lab configuration

Being an initial look at a completely new air traffic environment, it was important to have enough participants interact with the same traffic scenarios and human/automation integration conditions. Therefore, the lab communication architecture was modified to enable the parallel simulation of three decoupled scenarios in three separate clusters. Each cluster contained a simulation manager, a ghost ATC station, a supporting pseudo pilot station, a data collection station and the participant position. Figure 10 depicts the communication architecture. All support positions were almost entirely automated and required only minimal supervisory oversight to make sure the MACS stations were processing all received commands appropriately. The same scenarios were started at the same time on all three clusters and participants were presented with the same traffic problem and condition simultaneously. As a result, in each two-day experiment session, training and data collection for three participants could be conducted simultaneously creating a very efficient study environment.

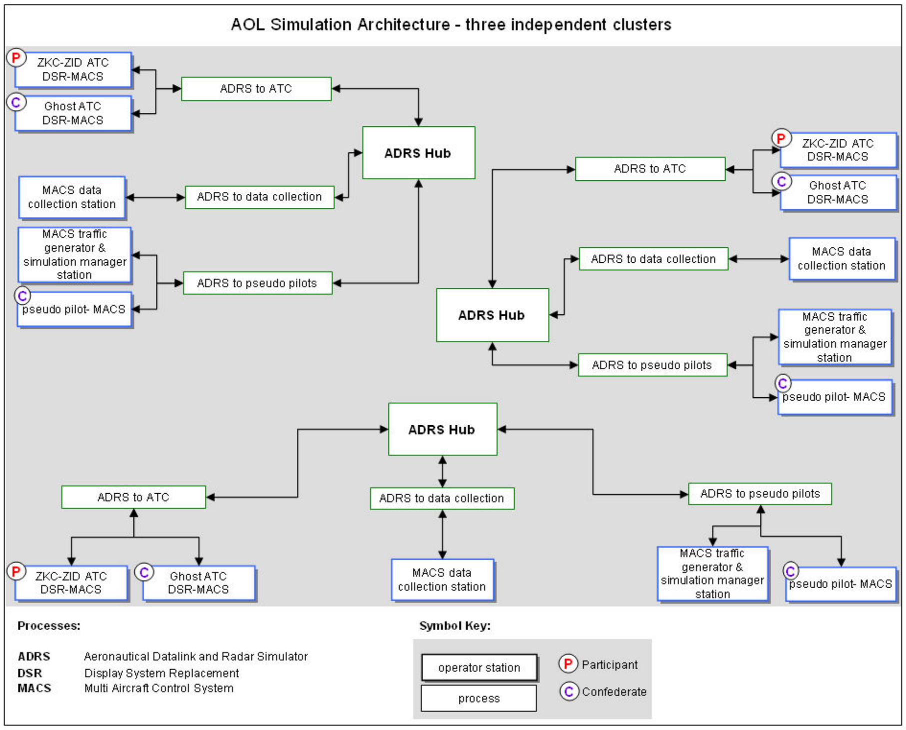

Figure 10. Communication infrastructure for part-task study on machine-based separation assurance. Three independent clusters with automated MACS support stations enable concurrent data collection for three participants.

B. Modifications to the controller workstation

The display modifications to go along with the added automation and the new allocation of roles and responsibilities between controllers and automation were accomplished through changes to MACS' configuration

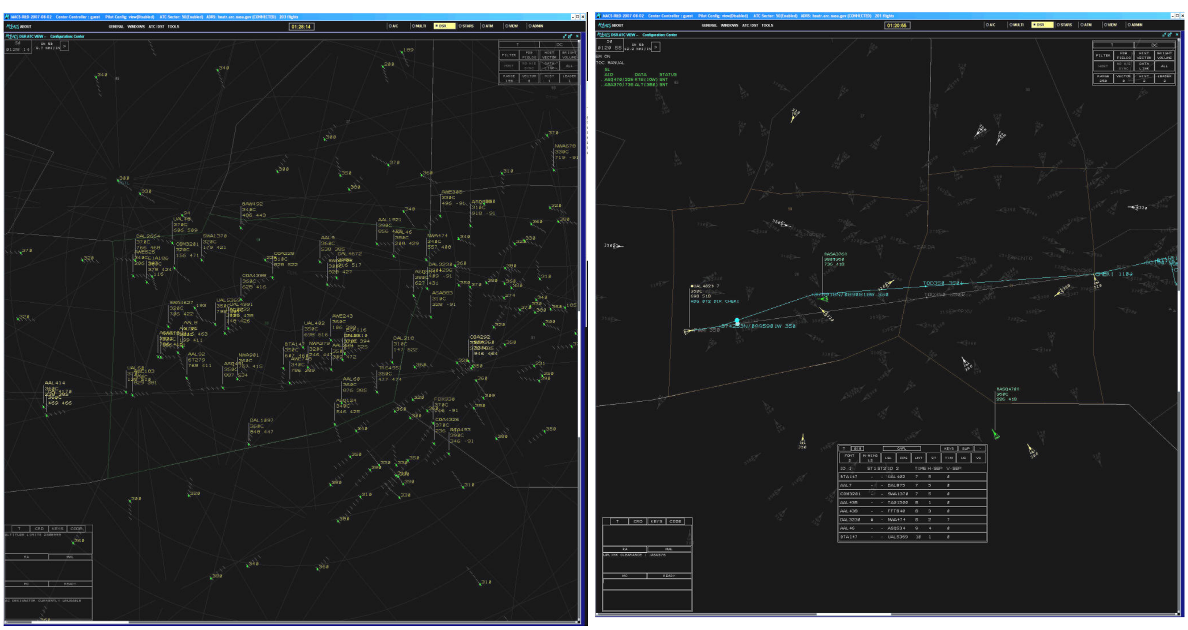

Figure 11. Display design for AAC part-task study. On the left is a current day DSR display as it would look with 3x traffic in a single sector. A prototype controller display with 3x traffic designed for working conflict resolutions in two combined sectors is shown on the right.

options. Most notably to the operators were the changes to the look and feel of the DSR screen. The MACS framework was used to configure a controller display for future air traffic operations that would be very different from what they are today. In a current-day DSR screen, the data block for each aircraft owned by a controller must be fully displayed while inside their sector, or whenever the controller has track control. Once an aircraft is handed off and outside of their sector, the controller can then collapse, or minimize, the data block of that aircraft in order to reduce clutter and possible confusion. When increasing traffic two and three times current-day levels, the display would become so cluttered with each aircraft's data block that the controller working the sector would spent nearly the entire time trying to de-clutter their display, leaving no time to deal with air traffic control tasks, such as separation assurance. The clutter would make it difficult to even identify an aircraft in conflict, severely constraining the participant's ability to conduct any reasonable job. In the left side of Figure 11 is shown what a DSR display would look like with three times the amount of current-day traffic for one sector.

As a result, changes were made to the DSR screen that support controllers managing separation assurance by creating conflict resolution trajectories under such high traffic volumes. These changes to the DSR look and feel were done with the configuration setup panels in MACS. The biggest change came from a set of rule-based behaviors assigned to the data blocks. As shown in the right part of Figure 11 and in Figure 12, assignable rules were defined to display the data blocks according to their conflict status:

1) If no conflict is detected, display as a limited data block in dark grey
2) If a conflict is detected between 9 and 12 minutes out, display as a limited data block in white
3) If a conflict is detected between 5 and 8 minutes out, display as a limited data block in yellow
4) If a conflict is detected less than 5 minutes out, display as a limited data block in orange

With the aircraft in conflict highlighted, the controller could then easily access that aircraft's full data block by clicking on the aircraft symbol.

Figure 12. Data block color-coding based on conflict status.

Incorporating the tool sets developed in previous AOL simulations, the full data blocks in the AAC simulation included a "portal" to access the trial-planning function. Integrated with a highly responsive conflict probe, the trial-planner gave the controller participants the ability to manually create conflict-free routes for all aircraft. These trajectories were combined with datalink, allowing the controllers to send the new routes directly to the aircraft as described in [1].

As a new feature, controllers were able to use the conflict list, the data block's portal, or the data block's altitude field to request an automation-generated conflict resolution proposal with a preference for a lateral, or an altitude maneuver, respectively. The "AAC"-generated solution was loaded as a trial-plan for review and uplink to the aircraft by the controller. Since it was presented as a trial-plan, controllers could also modify the automation-generated solution manually to "tweak" it. This interactive mode was seamlessly integrated into the general display philosophy and allowed for a straightforward human/automation interaction.

For an additional comparison condition, MACS was configured to resolve all conflicts automatically. The automatic resolution was triggered based on time-to-conflict. Once a loss of separation was predicted to occur within less than eight minutes, the resolution was automatically generated and sent to the aircraft three seconds later. This mode was used for analysis purposes by the researchers, with the aim of comparing conflict resolutions between the participants and the automation.

Since the first part of this study has just been completed, the data has not been analyzed and will be presented at a later occasion. The simulation itself went very smoothly, highlighting the differences and main properties of all conditions and traffic levels, as intended. Overall feedback by the participants on the display design, operational concept, and performance of the automation was very positive.

VI. Concluding Remarks

The Multi Aircraft Control System (MACS) is a simulation platform developed in the Airspace Operations Laboratory (AOL) at NASA Ames Research Center as a comprehensive research tool to increase the overall realism and flexibility of controller- and pilot-in-the loop air traffic simulations. This paper has presented a few select MACS applications demonstrating the capabilities to rapidly prototype new interfaces, displays, tools, and operational concepts for addressing the complex controller/pilot/automation integration crucial to the implementation of the Next Generation Air Transportation System (NextGen).

Acknowledgments

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