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Work-Centered Support Systems: A Human-Centered Approach to Intelligent System Design

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FOR THE COMMANDER

//SIGNED//

MARK M. HOFFMAN
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14. ABSTRACT

The Work-Centered Support System (WCSS) approach to human-centered computing focuses on analyzing and supporting cognitive and collaborative work. The WCSS for Global Weather Management (GWM), developed to support weather forecasting and monitoring in an airlift service organization, exemplifies this approach. The WCSS-GWM uses software agents embedded in work domain visualizations to support cognitive and decision-making processes, work artifact production, collaboration, and management of the multiple interwoven tasks that characterize work. It demonstrates and extends cognitive-engineering principles for effecting human-software agent interaction and WCSS concepts.

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PREFACE

The research documented in this technical report for the Global Air Mobility Advanced Technologies (GAMAT) program was sponsored by the Air Force Research Laboratory, Human Effectiveness Directorate, Sustainment Logistics Branch (AFRL/HESS), Wright-Patterson Air Force Base, OH. BBNT Solutions LLC performed the work under contract F33615-01-F-9062. Samuel R. Kuper (AFRL/HESS) was the program manager for the effort.

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The Work-Centered Support System approach to human-centered computing focuses on analyzing and supporting the multiple facets of work. The WCSS for Global Weather Management, developed to support weather forecasting and monitoring in an airlift service organization, exemplifies this approach.

A hallmark of *human-centered computing* (HCC) is its focus on domain practitioners and their field of practice.[1,2] Human-centered design depends on a deep analysis of a field's cognitive and collaborative demands and how people work individually, in groups, and in organizations to meet those demands.[3,4] The objective is to leverage what we know about human cognitive and collaborative processes to create systems that optimize the *affordances* (direct perception of meanings) and *effectivities* (knowledge-driven actions) for humans.[5]

We developed a software-agent-based system for weather forecasting and monitoring that exemplifies the HCC approach and demonstrates *work-centered support systems* concepts.[6–8] The WCSS paradigm offers an approach for incorporating software agent technology in a manner that helps the user keep his or her "head in the work" and reduces the possibility that software agent states or actions will surprise the user. To date, software-agent technology has focused largely on increased autonomy of individual software agents and increased coordination of activity among multiple software agents.[9] As the technology matures, we need to focus on how to integrate agents into teams that include both humans and agents and how best to deploy agents to support human work.[10,11]

Work-centered support systems

A distinguishing characteristic of WCSSs is that they focus on supporting all facets of work. Specifically, a WCSS includes

- *decision support* aiding problem solving and other cognitive work processes,
- *product development support* aiding deliverable work artifacts' production,
- *collaborative support* aiding team and colleague interactions, and
- *work management support* aiding the metacognitive activities entailed in prioritizing and managing multiple intertwined work activities (such as requirements for attention shift and remembering the number and state of tasks in process).

A WCSS attempts to integrate support for each of these areas through the principle of *joint aiding*—the coordinated use of direct and indirect aiding methods within a common, work-centered ontology.[7] A coordinated set of software agents that interact with the user and are clearly connected to or embedded in work domain visualizations provide direct aiding.

Indirect aiding is provided largely through the creation of work domain visualizations that reveal domain relationships, constraints, and affordances. By emphasizing the need to support all facets of work and to provide direct and indirect aiding, the WCSS paradigm falls squarely within the HCC tradition.

Designing a WCSS

We developed the *Work-Centered Support System for Global Weather Management* (WCSS-GWM) to support weather forecasting and monitoring in a military airlift service organization. Building a WCSS requires a development process that grounds system requirements in a deep understanding of the cognitive and collaborative demands of the work domain. We achieved this through close collaboration among cognitive and software engineers and end-user domain practitioners, all of whom were involved from the project's inception. The collective goal was to understand the workspace (work demands and practices in the environment) and stretch what we already knew how to do to build a new work environment—a collaborative effort in envisioning, creating, and refining a new workspace.

Our project's background

Traditionally, airlift pilots have been responsible for their own flight planning, including obtaining preflight weather briefings. The organization we worked with initiated a new approach to reduce the amount of time an aircrew must devote to these tasks. It created a flight manager (FM) position with the primary responsibility of planning and managing multiple flights, both preflight and en route. This includes obtaining a weather briefing and providing a complete flight plan to the pilot, including weather forecast information. The FM is a virtual crew member who supports the pilot.

Weather can significantly influence preflight and en route flight management decisions (for example, accelerating, delaying, or rerouting a flight because of unfavorable weather conditions). So, weather forecasters must work closely with the FM to evaluate weather conditions at the departure and arrival airfields and along the planned route. We focused on developing an intelligent system to aid near-term weather forecasting to support planning and managing airlifts.

Cognitive analysis

Our WCSS methodology emphasizes acquiring an understanding of work as practiced. Field observations and interviews intended to help us understand the cognitive and collaborative demands of the domain were an integral part of our WCSS-GWM development process.[12] We examined work practices in terms of decision making, product development, collaboration, and work management activities. These revealed aspects of cognitive and collaborative work that could be more effectively supported, which then guided the design of the WCSS-GWM architecture and displays.

We performed three site visits, each two to three days long and held approximately two months apart. During these visits, we interviewed forecasters, FMs, and senior personnel to understand workflow and elicit examples of the complications that can arise and increase task demands. We also observed FMs and forecasters as they handled actual flights during planning and en route phases to identify FM and forecaster activities and sources of complexity that the interviews didn't reveal. We sampled as broad a range of domain practitioners and situations as practical, including interviewing five or six individuals during each visit, interviewing individuals with differing levels of experience and expertise, and conducting observations over several time periods to sample different activity rhythms (morning and evening shifts as well as shift turnovers). Observations spanned routine and challenging cases. They revealed the intensive collaboration that occurs between FMs and forecasters when weather conditions such as severe turbulence or lack of anticipated tailwind require modification to planned flight routes.

> By emphasizing the need to support all facets of work and to provide direct and indirect aiding, the WCSS paradigm falls squarely within the HCC tradition.

We presented storyboards (rapidly developed prototypes) to FMs and forecasters for their comments, enabling them to actively participate in design. The storyboard prototypes embodied candidate aiding concepts and displayed increasing functionality and robustness with each site visit, reflecting what we'd learned from the prior visit. They provided a concrete vehicle to demonstrate our growing understanding and to obtain user feedback on the evolving aiding concepts' viability. They also provided a stimulus for raising additional domain constraints and complications that we'd need to accommodate.

A multidisciplinary team—including cognitive engineers experienced in domain analysis and user requirements specification and software engineers who would design and implement the software—conducted the field observations and interviews. The participation of both cognitive and software engineers facilitated dialogue among the team members and enabled close collaboration in the specification and design of the WCSS-GWM system architecture and user interface.

Workspace and work pattern observations

Typically, three trained forecasters are on duty each shift in the organization we studied. Two sit in a weather-forecasting room adjacent to and within sight of the FMs' area, and one sits in the flight management area to provide collaborative support to the FMs. The weather-forecasting room includes numerous workstations, each with two or three CRTs, and several wall-mounted TV monitors and large-screen displays that can be slaved to some of the workstation screens. As a matter of standard practice, the large-screen panels display loops of weather satellite imagery, focused on geographic regions of interest. They are also used to present weather briefings to FMs during shift changes, as well as to support forecaster collaboration.

The forecasters focus on near-term aviation weather forecasting—understanding and predicting weather conditions that will affect flights in the air and those scheduled to take off in the next 12 hours. Near-term forecasting requires acquiring, interpreting, and integrating multiple weather data types, including satellite imagery, airfield and other observations (such as pilot reports of turbulence), upper-air forecasts, and computer model projections from local and worldwide sources. These weather data types were typically available to the forecasters from separate Web pages or map displays, requiring forecasters to mentally integrate information from multiple disparate sources.

In many cases, the available data are incomplete, ambiguous, stale, or conflicting. Weather-forecasting expertise includes the abilities to look for convergence among multiple data types (to check that "things are lining up") and pursue additional sources of evidence to fill in missing data or resolve ambiguous or conflicting data. For example, a forecaster can increase confidence in a forecast by checking with a location in a predicted storm's path to confirm that the storm has materialized. Similarly, the forecaster can increase confidence in a turbulence prediction by checking certain kinds of satellite imagery and seeking pilot reports (PIREPS) confirming actual conditions.

We observed several cases where forecasters had to reconcile conflicting forecasts, including cases where the forecaster needed to call the forecast's source to understand the basis for a prediction. In at least one case, the forecaster had to advocate an alternative forecast. Being able to resolve ambiguous or conflicting weather data is critical because predicting severe weather has risk/benefit consequences. Being too conservative can mean serious delays or cancelled missions; being insufficiently conservative can result in costly mission diversions, plane damage, or even risk to life. To minimize the impact on mission objectives, forecasters are sensitive to both of these concerns and work intensely to refine their forecasts and communicate to FMs the basis of and level of confidence in weather predictions. They must also identify ways to work around real or anticipated weather hazards—for example, by selecting alternate takeoff or landing airfields or changing the takeoff time or flight route.

Our analysis revealed that FMs and forecasters operate as a team to manage the airlift missions in their work queue. The FM is the primary player, constructing flight plans, preparing crew papers, and monitoring the many details involved in ensuring each mission's success. The forecasters engaged in multiple activities:

- maintaining situational awareness of weather conditions in multiple geographic regions worldwide,
- preparing general forecasts for these regions and tailored forecasts for each mission,
- responding to requests and providing timely weather data to various parties in the organization (including pilots who call for weather updates),
- monitoring weather observations to assess their effects on current and upcoming missions,
- helping FMs develop options for working around hazardous weather to minimize its impact on mission goals, and
- negotiating with other weather-forecasting organizations regarding the appropriate interpretation of ambiguous weather data and advocating particular weather interpretations.

FMs and forecasters worked collaboratively to understand the consequences of unexpected situations (such as changing mission requirements or weather conditions) and determine appropriate action (such as delaying or rerouting a flight or changing the fuel load or cargo).

> Tools that enable more rapid recognition of changes in weather conditions and production of revised forecasts would enhance both forecasts' accuracy and timeliness.

Identifying leverage points—opportunities to provide support

Our analysis identified a number of leverage points or opportunities to more effectively support weather forecasting and monitoring. This provided the basis for defining work-centered support requirements.

Decision support. Forecasters can use support in collating and integrating information from multiple, disparate aviation weather sources, including forecasts, satellite imagery, real-time weather updates, and particularly flight plans for current and near-term flights. This can be accomplished by integrating the multiple weather sources on a single georeferenced map.[13] Providing an integrated visualization enables forecasters to more quickly derive and update a situation model of significant weather factors in their geographic areas of responsibility. This supports the general requirement for forecasters to achieve and maintain weather-related situational awareness so that they can make sound decisions. An integrated visualization provides more effective support for the cognitively challenging aspects of forecasting: identifying converging evidence in support of a forecast and identifying and resolving ambiguous or conflicting information.

Product development. The process by which forecasters update and revise forecasts is labor intensive, so they don't update them as often as they'd like. Tools that enable more rapid recognition of changes in weather conditions and production of revised forecasts would enhance both forecasts' accuracy and timeliness.

Collaboration support. The forecaster-FM team needs collaborative support in evaluating weather's impact on flight plans and making reroute decisions. Weather and flight information aren't well integrated. The forecaster has the best access to weather information, and the FM has the best access to planned and en route flights' status. Superimposing weather and flight information (for example, the flight route and organized tracks that constitute legal flight path options) on a single georeferenced map that the FM and forecaster can view simultaneously would let them visualize the weather's impact on a flight route and collaboratively formulate reroute options.

Work management support. Forecasters must monitor weather conditions in multiple geographic regions of interest and support planning and monitoring of tens of flights. Notifying the forecaster and FM of significant changes in weather conditions and the missions that weather changes will affect can help direct their attention to potentially high-risk flights. Further, mechanisms that support keeping track of missions to be monitored and easily shifting back and forth among them are important to support the multiple interwoven activities that characterize forecasters' work.

Using software agent technology to create a WCSS

The WCSS-GWM focused on monitoring the status of en route and near-takeoff missions with respect to weather conditions and on achieving and maintaining weather-related situational awareness for geographic regions of interest.

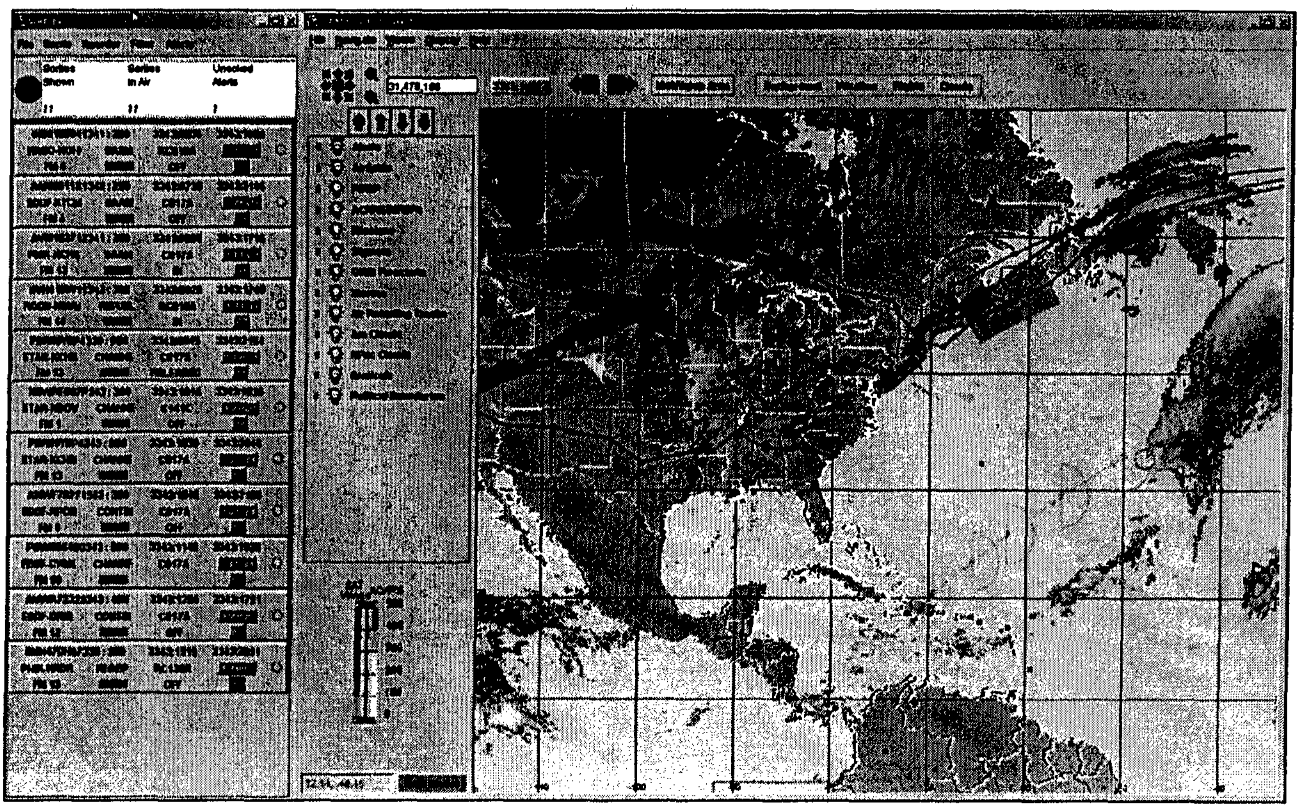

Figure 1. The Work-Centered Support System for Global Weather Management's map display and floating Sortie Palette.

Our investigation into how weather personnel performed these tasks suggested which weather data types would be useful. The weather personnel already used some of these data types. In some cases, weather personnel evaluated graphic images, and we'd have to analyze the underlying numerical data to achieve the same effect. To meet our design objectives, the WCSS-GWM required these functionalities:

- acquisition of real-time weather observations, such as PIREPS and automated observations of wind and turbulence information sent through the Aircraft Communication and Reporting System (ACARS).
- acquisition of worldwide airfield and upper-air forecasts produced locally and remotely. These include Significant Meteorological Information bulletins (SIGMETS), which describe areas with weather that's potentially hazardous to aviation; Meteorological Terminal Air Reports (METARS), which describe current surface weather observations at worldwide reporting stations; and terminal area forecasts (TAFs), which are bulletins that give surface weather forecasts for worldwide reporting stations.
- graphical integration of multiple data sources including maps, flight plans, forecasts, point observations, and satellite imagery. An important design requirement was the ability to easily overlay any subset of data types on the same georeferenced map for comparison purposes.
- automated comparison of real-time weather observations with user-defined geographical areas of interest (referred to as *watch areas*) and alerts to focus forecaster attention on operationally relevant changes in weather conditions. Achieving a general capability for an automated alerting process would be difficult. So, we limited alerting to specific, useful capabilities, such as generating an alert for any report from PIREPS or ACARS of turbulence or icing of at least a defined severity level in the defined region of interest (latitude, longitude, altitude, or time).
- automated and directed monitoring of individual missions and watch areas, as well as generation of alerts to focus user attention on changes in weather conditions that can affect flights.

The prototype we developed includes a centrally located, georeferenced-map-based visualization as a framework for providing direct and indirect aiding. Users can selectively superimpose a variety of weather and flight plan information on the map. Weather-related alerts generated by software agents are presented at their geolocations on the map. The display is built on top of OpenMap, an open-source, Java-based, geospatial display toolkit (see http://openmap.bbn.com). Figure 1 illustrates the WCSS-GWM's basic features.

The WCSS-GWM's "home view" is a map showing the geographical area of interest, surrounded by controls. The map controls let you pan, zoom, and change projections, while layer controls let you view multiple layers of flight and weather information on the map. You can place flight plans, PIREPS, ACARS, observations, SIGMETS, and satellite images on the map and remove them. An altitude slider control lets you filter observations by specifying the altitude.

You can access more details by hovering over an icon; for example, you can obtain a PIREP's text by placing the cursor over the PIREP symbol on the map.

A floating Sortie Palette lists all missions of interest and summarizes individual missions' status. It provides the abilities to highlight and locate specific missions and to sort and organize them to suit the work context. It also lets users maintain awareness of weather-related alerts, keeping track of which ones they've already viewed and which ones they must still deal with. Furthermore, it's integrated with the map display such that you can highlight problem notifications on the map with a simple button click on the palette. Thus, the Sortie Palette aids work management for work on a given mission or a set of missions.

Software agents' role

Software agents provide intelligent automation to directly support forecasters. The WCSS-GWM includes agents that monitor missions and geographic regions of interest and notify the forecaster when operationally significant weather changes occur. A key WCSS-GWM design element is that the forecaster can create, monitor, and modify these agents. For example, the forecaster can create an agent by drawing a polygon around a watch area on the map and specifying the agent behavior by setting parameters (desired altitude, start and stop time, hazard type, and severity to watch for). Later, the forecaster can modify the polygon's shape and position and modify the agent behavior by changing the parameters. Forecasters can also create and modify agents that monitor for weather changes around a flight path.

Figure 2 illustrates this ability to create and modify agents. The wide shading along a flight path indicates the geographic area an agent is monitoring. Similarly, the transparent geometric shapes off the eastern US coastline indicate the watch areas agents are monitoring. The Create Area and Edit Agent Parameters pop-up windows illustrate the abilities to create new agents and to view and modify the parameters that control agent behavior.

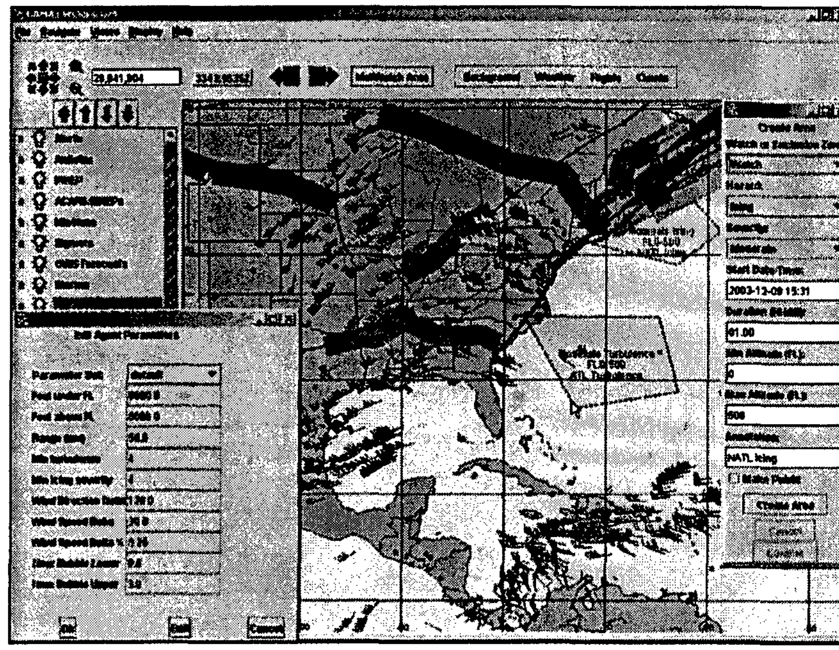

Figure 2. A screen shot illustrating the ability to create and modify software agents.

User (forecaster) creation of agents is an important aspect of a WCSS. Complex systems with many automation features, such as auto-assistance in different operational modes, can lead to machine-induced user errors[10] in which the user thinks the system is behaving in one way but the automation condition causes it to behave differently. System designers can mitigate this problem by providing users with the capability to create and set the conditions for an agent. Because of this involvement in specifying and activating the automation protocol, the user should have increased awareness of what service the automation provides.

The watch area agent in Figure 2 is expressed in work terms—a physical area to be watched, indicated by the polygon. Users don't have to translate from an agent icon to the weather-based semantic intent of what assistance the agent provides. They observe the agent directly in the work ontology, thereby reducing cognitive complexity and demand.

The WCSS-GWM contains three broad classes of agents. *Acquisition agents* acquire data from outside sources such as weather bulletins, ACARS, SIGMETS, satellite imagery, mission details, and flight plans. Each acquisition agent is responsible for a particular data type or source and periodically retrieves the latest data from that source (anywhere from once a minute to once every few hours, depending on how often new data are available). Furthermore, each acquisition agent signals other interested agents when it has retrieved new data.

Analysis agents analyze data that acquisition agents have retrieved to produce initial problem indications (individual turbulence or lightning strike reports, intersections of flight plans with SIGMETS, and so on). Forecasters trigger *region analysis agents* when they decide to monitor a geographic region for critical conditions (that is, to create a watch area) and then watch for observations matching given criteria. The presence of a current or upcoming flight mission automatically generates *mission analysis agents*, which watch for reports (such as PIREPS or ACARS) close to the flight plan (in latitude, longitude, altitude, or time) that significantly affect the mission.

Presentation agents, based on the analysis agents' results, decide what information to present to the user. These agents work on initial problem indications, clustering and prioritizing them to create a high-level presentation of problems. For example, the analysis agents might generate many related notifications that the presentation agents must aggregate into a single notification message to avoid an "alarm avalanche" problem.[14] Presentation agents also stage displays—that is, they retrieve enough of the right kind of data so that the information the user needs can be quickly rendered on the screen. We've implemented only a limited presentation agent capability (as shown in Figure 2), but in a full-scale WCSS-GWM implementation, these agents would have two additional responsibilities:

- displaying data at different levels of aggregation, depending on the user's role. For example, a supervisor might get only a top-level summary view of areas of turbulence, while the user responsible for a particular mission might see individual reports of turbulence close to that mission path. The presentation agent would aggregate the same underlying data to different levels for different users.

- displaying different data depending on the user's role. In a global system, multiple FMs and forecasters would split the globe into regions of responsibility. As analysis agents produced critical weather indications, a presentation agent would present this information only to interested users.

A consideration in the agent architecture design was to create a structure that the forecasters could understand, inspect, and modify. While software agent research has tended to focus on the high-level tasks delegated to agents and their level of autonomy, agent technology's value from a software development perspective is that software agents are small, independent chunks of software. Each addresses a small, unified set of tasks and is separately controllable and modifiable. In creating the agent architecture, we needed to structure the software so that the agents' capabilities would be meaningful to users in terms of their work domain. We configured the agents to mirror the basic terms of reference the users employ in addressing their work. This applies both with respect to the agents' functions (such as acquiring, analyzing, and presenting data) and to the domain objects the agents work on (such as missions, forecasts, and watch areas). Once the software is organized into domain-meaningful chunks implemented as agents, users can more readily observe and direct their operation.

Using D-OMAR to create agent-based systems

We built our agent system on top of the Distributed Object Model Architecture system, developed under the Air Force Research Laboratory's sponsorship (see http://omar.bbn.com). D-OMAR was initially an event-based simulator that included representation languages designed to facilitate research in human performance modeling.[15] It has evolved into a full-featured distributed software infrastructure that provides a broad range of services essential to agent-based system development. Agents must be created, be able to launch procedures that implement their services, and be retired or removed when no longer needed. A publish-subscribe protocol supports agent communication. In addition to the basic function of moving data between agents, the publish-subscribe capability plays an essential role in coordinating pairs or groups of agents' activities. An agent can also use the publish-subscribe protocol to coordinate the execution of its multiple proactive and reactive behaviors. We've found these language features essential to the rapid development of sophisticated agent behaviors.

Two implementations of D-OMAR exist: the original Lisp implementation, now known as OmarL, and the new Java implementation, OmarJ. We developed the WCSS-GWM using OmarJ. Software agents developed in either environment have similar capabilities; indeed, Java- and Lisp-based agents are interoperable. A procedural language supports agent behavior implementation. In OmarL, the Simulation Core language (SCORE) was built as an extension of the Lisp language itself. ScoreJ, a set of Java class libraries, provides a similar capability for Java implementations. Important language features such as race, join, and satisfy support the development of concurrent proactive and reactive procedures essential to individual agent behaviors. Time management features such as sleep support the scheduling of important services, and you can use them with concurrency control to specify time-out conditions. These language features, used in combination, can act as pattern matchers for events evolving in time. The languages also support the priority-based mediation of contention between specified subsets of procedures.

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The WCSS-GWM's status

The WCSS-GWM is in the late stage of development. We've installed it on several workstations at the airlift service facility, and forecasters are using it. Users have reported several cases where they successfully rerouted flights on the basis of information provided by the WCSS-GWM.

Implications of using agent technology

Designing the WCSS-GWM required us to consider a number of questions related to integrating software agents into human-centered computing.

Observability and directability

A growing body of cognitive-engineering literature is showing that for automated agents to be effective, they must act as team players.[10,11,16] For software agents to become team players, you need to design in two fundamental characteristics from the beginning—*observability* and *directability*. Users must be able to see what the automated agents are doing and understand what they'll do next relative to the task's state. They also need to be able to control and redirect the software agents as task requirements change.

We designed the WCSS-GWM agent-based architecture with these objectives in mind. The georeferenced map provides a common-ground representation of the current situation that's available to both humans (FMs and forecasters) and software agents. Furthermore, the user can see and control agents' activities—the display presents the geographic area the software agents are monitoring, and the user can modify it. Similarly, the forecaster can inspect and modify the weather parameters that the agents are monitoring and the trigger points for alerts.

Software agents' role in human-centered systems

Our discussion of agents in the WCSS-GWM points to their multiple roles in human-centered systems' development. At the software development level, agent technology is valuable because the agents are small, independent "chunks" of software, each of which addresses bounded tasks. Software agents can be controlled and modified separately, which greatly facilitates software development, maintenance, and upgrades.

From a work-centered perspective, agents are useful because they enable the development team to organize software components around the elements of work. A detailed domain analysis lets the team map out the work requirements and systematically allocate tasks to humans and software agents as appropriate. In the domain of weather forecasting to support flight management, the kinds of work that humans can allocate to software agents include "watch this region of the world and let me know of any weather problems that arise" (region analysis agents), "watch this mission for me and let me know of any problems that arise" (mission analysis agents), or even "watch this weather system" or "interpret this weather pattern" (weather-centered agents, which we have yet to implement), freeing human attention resources for other tasks.

A corollary of structuring agents in work domain terms is that the agents give us a concrete vocabulary of concepts and metaphors (agents as subordinates to whom you can assign specific tasks) that software and cognitive engineers and users can share. This facilitates communication and enables closer collaboration during system design.

Software agents: Behind the scenes or up front?

Closely related to the question of software agents' role in human-centered systems is the question of their visibility in the interface. We continue to struggle with the extent to which (and conditions under which) software agents should have an explicit screen presence. Should we treat software agents as convenient chunks of code that underlie system functionality but have no explicit presence in the user interface, or should they be explicit to let users interact with them?

Multiple stances are possible on this question. At one extreme, you could argue that agents are a powerful tool for software implementation but that users should never see or hear about them as such. Arguments for this position include concerns that users might ascribe a greater degree of expertise, competence, and autonomy to the agents than is warranted, leading them to overly trust the agents. Conversely, ascribing more autonomy to the agents could also cause users to unjustifiably mistrust or even fear them. At the other extreme, you could argue that if agents have a screen presence and even a personality (such as the animated Microsoft paperclip), users can more readily grasp their functionality, seeing them as assistants or subordinates to whom they can delegate tasks.

For the WCSS-GWM, we chose a middle ground. Some agents are visible in the user interface, while others operate behind the scenes. Agents with a visible presence are organized around domain work: the forecast, region, and mission analysis agents. Users delegate work to these agents that they would otherwise have to do themselves. The agents' presence in the user interface lets users monitor and control their performance. Our focus was on letting users understand, observe, and control the agents' behavior. However, we made no attempt to personify these agents. Nothing marks them as agents on the screen, and they have no personality or animated presence. Rather, we adopted a work-centered perspective where users interact with the interface and monitor and delegate tasks to agents in the context of performing their work.

Other agents in the WCSS-GWM remain predominantly behind the scenes, but users can access them should the need arise. For example, although the data acquisition agents operate out of sight most of the time, forecasters can bring up displays letting them inspect and modify the agents' performance as necessary. This becomes particularly important for diagnosing agent behaviors (for example, if a data source accessible over the Web goes down or if data become corrupted or stale) or tailoring agent behaviors to new circumstances (for example, to add or modify a data source).

Finally, still other agents execute software task elements, but users can't see or control them. This category includes the presentation agents, where a need for user interaction with the agents hasn't yet emerged.

We expect that the dialogue among users and cognitive and software engineers couched in terms of workflow for users and software agents will contribute to improved human-centered system design.

Fostering collaboration in system design

We found that an additional benefit of software agent technology is its potential to facilitate collaboration among users and cognitive and software engineers. The adoption of object-oriented design techniques over the last 10 to 15 years has improved communication among software and cognitive engineers and end users by providing easily understandable descriptions of the domain objects' software implementation and small-scale behavior. However, these descriptions have, at times, fallen short in providing the user with a clear understanding of large-scale system behavior—how objects hook together to produce the desired system results. As a system increases in complexity, the user can easily lose the big picture of how objects work together, with the result that collaboration between the user and the software development team effectively stops.

The agent architecture provides the potential for user-accessible descriptions not only of domain objects but also of workflow and large-scale interactions between domain objects. All members of the team can understand and contribute to the software's design. We expect that the dialogue among users and cognitive and software engineers couched in terms of workflow for users and software agents will contribute to improved human-centered system design.

The WCSS-GWM exemplifies and expands upon HCC concepts. It embodies WCSS concepts that emphasize the need to support the multiple facets of individual cognitive and collaborative work through the integration of software agents that support data acquisition, analysis, and visualization. We successfully transitioned the WCSS-GWM into the user organization, where it underwent a formal evaluation that produced highly favorable results.[17] We're continuing our research program to develop and exercise WCSS design concepts and principles through developing and evaluating WCSS applications. Our new research effort targets the broader enterprise of flight mission planning and execution.

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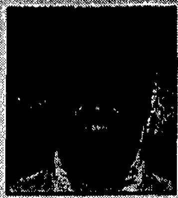

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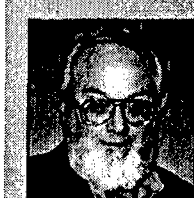

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References

1. Hoffman, P.J. Hayes, and K.M. Ford, "Human-Centered Computing: Thinking In and Outside of the Box," *IEEE Intelligent Systems*, vol. 16, no. 5, 2001, pp. 76–78.
2. E.M. Roth, E.S. Patterson, and R.J. Mumaw, "Cognitive Engineering: Issues in User-Centered System Design," *Encyclopedia of Software Engineering*, 2nd ed., J.J. Marciniak, ed., Wiley-Interscience, 2002, pp. 163–179.
3. K.J. Vicente, *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*, Lawrence Erlbaum Associates, 1999.
4. R.R. Hoffman and D.D. Woods, "Studying Cognitive Systems in Context: Preface to the Special Section," *Human Factors*, vol. 42, no. 1, 2000, pp. 1–7.
5. R.R. Hoffman, J.W. Coffey, and K.M. Ford, *The Handbook of Human-Centered Computing*, tech. report, Inst. for Human and Machine Cognition, Univ. of West Florida, 2001.
6. R.G. Eggleston and R.D. Whitaker, "Work-Centered Support Systems Design: Using Organizing Frames to Reduce Work Complexity," *Proc. Human Factors and Ergonomics Soc. 46th Ann. Meeting*, Human Factors and Ergonomics Soc., 2002, pp. 265–269.
7. R.G. Eggleston, "Work-Centered Design: A Cognitive Engineering Approach to System

Design," *Proc. Human Factors and Ergonomics Soc. 47th Ann. Meeting*, Human Factors and Ergonomics Soc., 2003, pp. 263–267.

8. M.J. Young, R.G. Eggleston, and R.D. Whitaker, "Direct Manipulation Interface Techniques for Interaction with Software Agents," *Proc. NATO/RTO Symp. Usability of Information in Battle Management Operations*, North Atlantic Treaty Organization Research and Technology Organization, 2000, pp. 19-1–19-10; ftp://ftp.rta.nato.int/PubFulltext/RTO/MP/RTO-MP-057/MP-057-19.PDF.

9. N. Jennings and M. Wooldridge, "Software Agents," *IEE Review*, vol. 42, no. 1, 1996, pp. 17–20.

10. K. Christoffersen and D.D. Woods, "How to Make Automated Systems Team Players," *Advances in Human Performance and Cognitive Engineering Research, 2: Automation*, E. Salas, ed., Elsevier, 2002, pp. 1–12.

11. J. Malin, "Preparing for the Unexpected: Making Remote Autonomous Agents Capable of Interdependent Teamwork," *Proc. XIVth Triennial Congress Int'l Ergonomics Assoc. and 44th Ann. Meeting Human Factors and Ergonomics Soc.*, Human Factors and Ergonomics Soc., 2000, pp. 1-254–1-257.

12. E.M. Roth and E.S. Patterson, "Using Observational Study as a Tool for Discovery: Uncovering Cognitive and Collaborative Demands and Adaptive Strategies," *How Do Professionals Make Decisions?* H. Montgomery, R. Lipshitz, and B. Brehmer, eds., Lawrence Erlbaum Associates, 2005, pp. 379–393.

13. R.R. Hoffman, "Human Factors Psychology in the Support of Forecasting: The Design of Advanced Meteorological Workstations," *Weather & Forecasting*, vol. 6, no. 1, 1991, pp. 98–110.

14. D.D. Woods, "The Alarm Problem and Directed Attention in Dynamic Fault Management," *Ergonomics*, vol. 38, no. 11, 1995, pp. 2371–2393.

15. S.E. Deutsch, "Interdisciplinary Foundations for Multiple-Task Human Performance Modeling in D-OMAR," *Proc. 20th Ann. Conf. Cognitive Science Soc.*, Lawrence Erlbaum Associates, 1998, pp. 303–308.

16. E. Roth, J. Malin, and D. Schreckenghost, "Paradigms for Intelligent Interface Design," *The Handbook of Human-Computer Interaction*, 2nd ed., M. Helander, T. Landauer, and P. Prabhu, eds., Elsevier, 1997, pp. 1177–1201.

17. R.G. Eggleston, E.M. Roth, and R. Scott, "A Framework for Work-Centered Product Evaluation," *Proc. Human Factors and Ergonomics Soc. 47th Ann. Meeting*, Human Factors and Ergonomics Soc., 2003, pp. 503–507.