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Developing an Embedded Method to Recognize Human Pilot Intentions In an Intelligent Cockpit Aids for the Pilot Decision Support System[+]

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ABSTRACT

Several recent aircraft accidents occurred due to goal conflicts between human and machine actors. To facilitate the management of the cockpit activities considering these observations, a computational aid, the Agenda Manager (AM) has been developed for use in simulated cockpit environments. It is important to know pilot intentions performing cockpit operations accurately to improve AM performance. Without accurate knowledge of pilot goals or intentions, the information from AM may lead to the wrong direction to the pilot who is using the information. To provide a reliable flight simulation environment regarding goal conflicts, a pilot goal communication method (GCM) was developed to facilitate accurate recognition of pilot goals. Embedded within AM, the GCM was used to recognize pilot goals and to declare them to the AM. Two approaches to the recognition of pilots goals were considered: (1) The use of an Automatic Speech Recognition (ASR) system to recognize overtly or explicitly declared pilot goals, and (2) inference of covertly or implicitly declared pilot goals via the use of an intent inferencing mechanism. The integrated mode of these two methods could overcome the covert goal mis-understanding by use of overt GCM. And also could it overcome workload concern with overt mode by the use of covert GCM. Through simulated flight environment experimentation with real pilot subjects, the proposed GCM has demonstrated its capability to recognize pilot intentions with a certain degree of accuracy and to handle incorrectly declared goals, and was validated in terms of subjective workload and pilot flight control performance. The GCM communicating pilot goals were implemented within the AM to provide a rich environment for the study of human-machine interactions in the supervisory control of complex dynamic systems.

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INTRODUCTION

In modern aircraft, the human pilots are no longer the only actors that control the aircraft and its systems. Machines, such as the autopilot and flight management system, also play an active role in control. In fact, several recent accidents occurred due to goal conflicts between human and machines. To facilitate the coordination of these actors, a computational aid called the AgendaManager(AMgr) is being developed. The AMgr, which operates in a part-task simulator environment, attempts to facilitate the management of goals the actors are trying to accomplish and the functions being performed to accomplish them. To provide accurate knowledge of pilot goals for the AMgr, a goal communication method (GCM) was developed. The embedded GCM recognizes explicit and/or implicit pilot goals and declares them to the AMgr. This paper presents the development, architecture, operation, and evaluation of the GCM.

A goal is a desired aircraft or aircraft subsystem state or behavior. For example, climb to 9000 feet′ or restore fuel pressure to right engine′ are goals. A *function* is an activity performed to achieve a goal. Goals are declared and functions are performed by *actors*. Human actors are pilots. Machines include autoflight and flight management systems (FMS). An *agenda* is a set of goals and functions. *Agenda Management* (AMgt) is a high level function performed by the flightcrew that involves

1. assessing the goals of all actors, removing those that are achieved, inappropriate, or inconsistent;
2. assessing the functions being performed to achieve those goals to see that satisfactory progress is being made towards achieving the goals;
3. prioritizing the functions, based on the importance and urgency of the goals and the status of the functions; and
4. allocating actor attention to the functions in order of assessed priority.

Ideally, AMgt is performed continuously by the flightcrew, so that all appropriate goals are achieved and that the higher priority functions are performed before the lower priority ones. In fact, that does not always happen. In analyses of 324 National Transportation Safety Board aircraft accident reports and 450 Aviation Safety Reporting System aircraft incident reports, we found that improper AMgt contributed to 76 (23 %) aircraft accidents and 231 (49 %) aircraft incidents (Chou et al, 1996).

As one possible approach to dealing with this problem, we are developing an experimental, computational aid to facilitate AMgt called the Agenda-Manager (AMgr). The AMgr operates in a part-task simulator environment, which is described below. It is an agent-based system made up of a collection of software modules called agents. Each agent represents some entity in the simulated flightdeck environment.

System agents represent aircraft systems, such as engines and the fuel system. Each system agent maintains current state information on its system, such as engine speed or fuel pressure, and detects system faults, such as engine fires or fuel pressure drops.

Goal agents represent actor goals. Each goal agent is capable of recognizing the conditions necessary for goal achievement. Additionally, goal agents recognize goal conflicts, such as would occur when the pilot's goal was to climb to 9,000 ft but the autoflight system's target altitude was inadvertently set to 8,000 ft.

Function agents represent the functions being performed to achieve the goals. A function agent records the status of the function and assesses function performance. For example, a climb to 9,000 ft' function agent knows that its function has a high priority (because altitude control is critical to flight safety) and can determine if the aircraft's altitude is changing towards the 9,000 ft target value.

Actor agents are a special kind of system agent representing actors. The autoflight agent keeps track of the autoflight system's goals by noting its modes and target values and instantiating goal agents. The flightcrew agent keeps track of the simulator pilot's goals in a manner described below.

The AMgr interface consists of a display that informs the pilot of goal conflicts and the status of each function, thereby facilitating AMgt. As the pilot flies the simulator, either manually or by using the autoflight system, system agents monitor aircraft and aircraft system state, and when faults are detected, instantiate goal agents for goals to correct them. Actor agents recognize actor goals to control the aircraft and instantiate corresponding goal agents. Goal agents check for goal conflicts and inform the pilot of any via the AMgr display. Function agents continually monitor the progress of functions to achieve the goals and inform the pilot if any are not being performed satisfactorily. The pilot is thus informed of the state of the simulated flightdeck environment and AMgt is facilitated.

But this process can work only if the pilot can make his/her goals known to the AMgr. This is a special case of the human-machine goal communication problem. In fact, it is often difficult for the human actor to efficiently describe the complete set of his/her goals to a machine such as the AMgr. That is, the human actor has an explanation problem with respect to the machine. In such a complex, dynamic domain as aviation, human ability to explain intentions to the intelligent system is highly constrained by both time and the expressive capabilities of a non-textual interface (Hammer, 1984; Hoshstrasser, 1991). Thus, recognition of pilot goals by machines has become an important safety issue as the use of automation increases in modern aviation systems.

Goal communication consists of the sharing of goal representations between human actors and intelligent machines in overt (explicit) or covert (implicit) forms that both the human and the machine readily understand. To design a goal communication framework for the control of an avionics system, it is increasingly important and useful to distinguish between overt and covert channels of communication.

Overt Goal Communication

Overt goal communication is an activity which allows the human actor to explicitly declare goals to a machine, such as the AMgr. One set of general alternatives consists of such standard communication media as the control yoke, buttons and switches, a keyboard, a touch panel, a mouse, and/or voice commands. For example, the human actor communicates a goal to the autopilot (A/P) subsystem via the mode control panel (MCP), which consists of several interrelated knobs and buttons. If the human actor wants to engage the autopilot, then the goal is stated explicitly by simply activating the A/P switch on the MCP. Or, the human actor may tell the flight management system (FMS) by keystrokes on the Control Display Unit (CDU) to follow a certain flight path, and the FMS responds by informing the human actor of the estimated time of arrival and rate of fuel consumption. Finding these estimates acceptable, the human actor explicitly instructs the FMS to implement the plan via the CDU. Standard input devices such as buttons and keyboard, used as overt communication media, often fail to recognize pilot goals directly and accurately because human pilots are fallible in their operation of buttons and switches, and because the pilots may experience additional cognitive loading to perform the operations.

All activities that declare a pilot's goals explicitly are considered to be explicit goal communications, even should such communications imply covert communications. For example, if the pilot should push the flight level change switch on the MCP to the on position, the activity itself is explicit goal communication, since the pilot has explicitly declared the goal of changing the altitude. At the same time, such a goal would automatically imply the holding of current heading and to trigger vertical speed modes. Goals for the heading hold and vertical speed modes will be implicitly declared from the implicit goal communication method.

Although the technology for speech interaction between humans and machines is by no means perfect, Automatic Speech Recognition (ASR) technology has received increased attention as an input means for direct and accurate overt goal communication. And despite the fact that current ASR technology has focused heavily on telecommunication applications such as voice activated telephone services, ASR is considered to be a promising method to declare pilot goals in a wide range of airborne environments, from helicopters and military jets (Mountford and North, 1980; Reed, 1985; Williamson et al., 1996) to civil aircraft (Starr, 1993). The application domain of flying an airplane is recognized as being potentially challenging to the use of ASR, since it exhibits some attributes that characterize adverse environments for ASR, such as high noise levels, high acceleration forces, and extreme levels of workload and stress (Williamson et al., 1996; Baber and Noyes, 1996). Nevertheless, ASR has been increasingly explored in the aviation domain not only because of its potential to reduce pilot workload; ASR permits eyes-and hands-free interaction with flight control systems and allows pilots to maintain head-up flight with hands on throttle and stick control. The potential exists also because of the fact that pilots are consistently communicating their goals verbally with air-traffic controllers and other flightcrew members, and because ASR technology is advancing rapidly.

Covert Goal Communication

The control actions of the pilot as he/she controls the aircraft by means of yoke, rudder pedals, throttles, and other controls implicitly carry within them information about the pilot's goals. Such goal information is available to and could be interpreted by an intelligent machine, such as the AMgr. This form of goal communication is covert in the sense that the human need not be conscious of the information transformation process. There are two primary reasons for trying to use covert goal communication. The first reason is to avoid the workload associated with overt communication. For example, if the machine could be enabled to covertly assess the human actor's intentions, then the human would not be distracted from other activities for the purpose of supplying this information. The second motive for the use of covert goal communication is based upon the possibility that, at certain times or in certain situations, it will not be possible to communicate goals overtly due to the fact that hands and voice are fully occupied with other, safety critical activities. To communicate covertly or implicitly with an intelligent aid in a highly dynamic system, the human actor simply performs procedural steps and a model-based intent inferencer infers goals from the procedural actions (Gerlach et al., 1995; Onken and Prevot, 1994; Geddes, 1985, 1989; Mitchell, 1987; Rubin et al., 1988). In other words, covert communication models are embedded within the intent inferencer and compared with human actions in an attempt to infer what the human's goals are.

Integration of Overt and Covert Goal Communication

Whereas covert goal communication imposes little or no additional workload upon the human actor, control actions can be ambiguous with respect to pilot intent, and misunderstanding of pilot goals by an intent inferencer is a real possibility. And though a misunderstanding poses little risk in experimental laboratory studies, it could be catastrophic in more realistic environments. On the other hand, overt goal communication by voice or manual means imposes additional workload and may interfere with safety critical activities. A possible solution to this dilemma is the integration of overt and covert goal communication. Hopefully, such an integrated method would offer the reliability of overt communication and the low workload requirements of covert communication.

Research Objectives

The principal goal of this research was to develop an integrated method of overt and covert (explicit and implicit) goal communication, to be embedded within the AMgr to facilitate AMgt performance. The objectives of this experimental investigation were to

1. develop a goal communication method (GCM) to recognize pilot goals based upon the integration of implicit (covert) as well as explicit (overt) modes of communication and
2. evaluate the methodology in the context of a real-time flight simulation environment with respect to

    - GCM accuracy,
    - GCM speed,
    - user satisfaction with GCM,
    - workload imposed by GCM, and
    - pilot flight control performance while using GCM.

Method

The integrated overt/covert GCM was developed, implemented, and evaluated in a real-time, part-task flight simulation environment. The simulator consisted of aerodynamic and autoflight models derived from the NASA Langley Advanced Civil Transport Simulator, primary flight displays derived from the NASA Ames Advanced Concept Flight Simulator, and subsystem models and synoptic displays developed at Oregon State University. The integrated flight simulation environment, implemented on Silicon Graphics Indigo-2 UNIX-based workstations, provided a part-task simulator that modeled a two-engine turbojet transport aircraft.

While it is straightforward for the AMgr to recognize machine goals by simply noting modes and target values, recognizing human pilot goals is not so simple. The Goal Communication Method (GCM) was developed for this purpose. The GCM is embedded in the AMgr for the recognition, inferencing, updating, and monitoring of pilot goals. It uses both overt (explicit) and covert (implicit) methods of goal communication.

Overt (Explicit) Goal Communication

To declare pilot goals overtly or explicitly, the verbal modality was employed using a commercial automatic speech recognition system (ASR). Using the ASR, the subject pilots called out their goals via microphone. The overt GCM framework consisted of two main parts. One was to recognize the goals from the ASR system process and the second was to declare the recognized goals to the AMgr.

While a pilot is performing flightdeck operations, he/she communicates with an air traffic control (ATC) controller, readily facilitating the detection of his/her goals. Since it is a legal requirement that the pilot read back ATC clearances, pilot goals concerning the control of the aircraft's heading speed, and altitude can be recognized by monitoring these clearance acknowledgments. For example, if ATC issues the clearance "OSU 037, climb to 9000," the pilot acknowledges the clearance with a response "Roger, climb to 9000, OSU 037," and an ASR system could recognize the pilot's utterance and declare a "climb to 9000 ft" goal to the AMgr.

The ASR system used for this research was a Verbex VAT31 installed in an IBM PC compatible personal computer. The VAT31 has a 40 MHz Digital Signal Processor (DSP) running under DOS and continuous and speaker-dependent capabilities. The Verbex grammar definition file defined vocabulary and grammar for a subset of pilot-to-ATC controller communication. Subject voice pattern files was created using the voice recognizer training process. As utterances were made by the subjects, the encoded form of verbally declared goals was sent through an RS232 serial port to the computer running the AMgr, in which the goals were parsed, declared, and stored.

Accuracy in the recognition of pilot goals is very important. Although accuracy depends to a considerable degree upon current ASR technology, careful human factors engineering of several system design aspects helped to increase recognition accuracy; for example, vocabulary selection, user and recognizer training, and visual and audio feedback (Cha, 1996).

Covert (Implicit) Goal Communication Method

While pilot goals were recognized via overt means when communicating with the ATC controller, they were also implicitly inferred from operational and/or other factors, such as the pilot actions of moving the control stick. This method for recognizing goals is a form of covert goal communication. The covert method was implemented to avoid the workload associated with overt goal communication. To build dynamic representations of current pilot goals, the inference logic for the hypothesized current pilot intentions was based upon four components;

1. pilot actions using sensed input (e.g., throttle, stick, landing gear control),
2. aircraft state information,
3. flightdeck procedures, and
4. overtly declared goals.

With knowledge of the four components, for each goal a script was constructed as a data-driven knowledge source. The script consisted of a representation of a loosely ordered set of pilot actions to carry out the goal shown in Table 1.

Given the current state of the above component variables and flight phases, GCM tried to interpret pilot actions based upon script-based reasoning processes depicted in Figure 1. If the action could be explained by an active script, the corresponding active goal

```
speedScript
. . . .
overtTargetSpeed isNil ifFalse:[inferredTargetSpeed := overtTargetSpeed].
. . . .
action = #thrustLeverUp
      ifTrue:
          [phase = #beforeTakeoff
               ifTrue:
          [inferredSpeedGoal := #maintainTakeoffSpeed.
           inferredTargetSpeed := rotateSpeed.]
          ifFalse: [inferredSpeed := #maintainSpeed].
          inferredTargetSpeed = nil ifTrue:[inferredSpeedGoal := #increaseSpeed]
  ^self].
. . . .
inferredSpeedGoal := #notUnderstoodPilotAction.
^self
```

Table 1. An Example of Active Speed Script

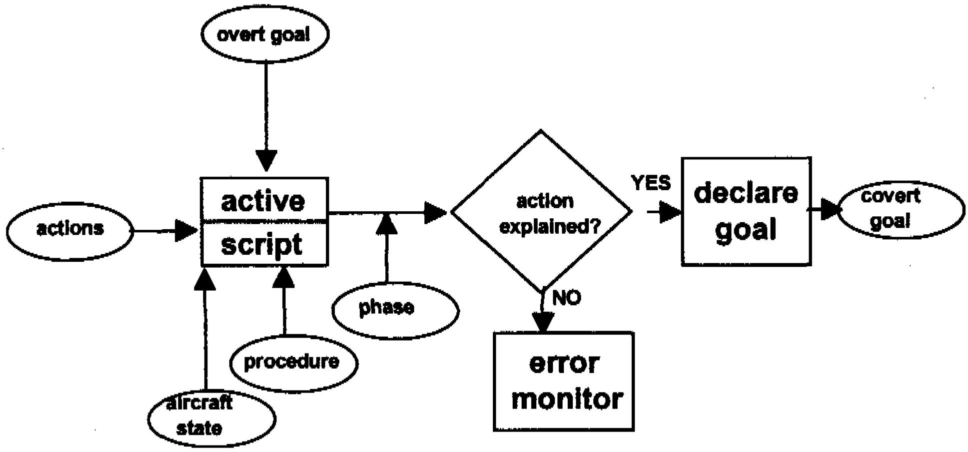

Figure 1. Covert GCM Process

was recognized and declared by the intent inferencer, which represented a process model using a blackboard problem-solving method. The knowledge source in this blackboard frame work consisted of a rule-based representation of goals and corresponding scripts for the part-task simulation domain. If the actions were not predicted by the active script, then the

GCM would ask the pilot to ignore the covert GCM and declare his or her goal explicitly using overt GCM.

Evaluation of the GCM

An evaluation of the GCM was conducted to ensure that the system correctly recognized the intentions of the human actor. In other words, the evaluation provided a measure of how well the GCM recognized pilot goals or intentions and how the GCM affected pilot performance. In a laboratory experiment using human subjects, this evaluation process demonstrated GCM effectiveness in terms of accuracy, speed, user satisfaction, and workload for the recognition of pilot goals within a simplified version of the AMgr.

Subjects The GCM was evaluated by 10 licensed general aviation pilots. Although most did not have commercial licenses and were not initially familiar with the electronic displays used in the simulator, all had some instrument flying knowledge and experience in controlling and monitoring aircraft altitude, speed, and heading. All of the subjects also had experience in air traffic control (ATC) communication.

Procedures To measure GCM effectiveness in terms of accuracy and workload, subjects were required to fly a simulated Eugene-to-Portland, Oregon scenario which involved declaring goals and performing tasks to control altitude, heading and speed manually. The autoflight system was not used. Using the same scenario with the same conditions, one experiment was performed running with the GCM and a second without the GCM. The subject pilots called out their goals explicitly using a headset microphone. Speech patterns were collected from the subjects concurrently, as they verbalized their intentions, actions, and problem-solving activities while operating the flight simulator. While they were flying, subjects were supposed to read back ATC commands immediately after they were heard. If they failed to declare their goals verbally, they were asked to repeat their goals until the overt GCM recognized them. The successfully declared goals were displayed on the AMgr displays. The subjects also removed their goals verbally whenever this was required.

The subject goals were also declared and recognized via covert GCM, which employed the intent-inferencing mechanism based on aircraft states, subject control actions, and verbally-declared active goal as described above. Whenever the subjects took actions using thrust levers or control buttons and levers, the GCM inferred, interpreted and displayed the goals. GCM compared the subject's actions with the current active script. If the actions matched the script, the actions were explained and the corresponding goal was inferred. Whenever the subjects were aurally alerted by the GCM that their actions could not be understood, they were asked to remove the ambiguity by taking a corrective action. If the GCM understood the corrective action, the ambiguity was resolved. If the covert GCM still failed to recognize the goal correctly, subjects were required to declare the goal verbally using overt GCM.

To measure the subject's perceived workload, the NASA-TLX (task load index) multi-dimensional subjective measure was used (Hart & Staveland, 1988). To facilitate accurate and objective experimental analysis, the entire flight simulation was videotaped.

RESULTS

Recognition Accuracy

GCM accuracy was measured statistically using confidence-interval estimation to determine accuracy. With the assumption of normality and a random sample of size 8 for recognition accuracy, we can say with a level of confidence of 95% that the average 91% of the overtly declared goals after the first utterance, and 99% of the covertly declared goals were successfully recognized. Similarly, at least 93% recognition accuracy was obtained by the integrated method of covert and overt GCM. When overtly declared goals were not recognized after the first utterance, recognition accuracy after the second (corrective) utterance was 99% (Cha, 1996). It is technically difficult to obtain 100% accuracy. Thus, if we accept the cost of the trials compared to the benefit of employing GCM, the GCM being considered can be used accurately as an embedded method to communicate pilots goals within the cockpit task simulation environment.

Comparison of workload

The objective of measuring workload was to know if any additional workload was imposed on subjects using GCM. It was assumed that the differences of $n = 8$ paired observations were normally and independently distributed random variables with mean μ_D and variance σ_D^2. The null hypothesis was that there was no additional workload when subjects used GCM. From the results shown in Table 2, the null hypothesis cannot be rejected. Therefore, it may be safely concluded that no extra workload was imposed by GCM.

Comparison of pilot flight control performance

The objective of measuring pilot performance in controlling flight was to know whether GCM interfered with pilot performance in controlling flight. Table 3 compares the data collected with and without GCM as a percentage of satisfactory performance. With the assumption of normality, the null hypothesis that there was no difference between performance in controlling speed, altitude, and heading with or without the GCM could not be rejected.

Table 2. Workload comparison

legs	takeoff & climb			cruise & descend			descend & approach		
	w/GCM	w/o GCM	difference	w/GCM	w/o GCM	difference	w/GCM	w/o GCM	difference
mean	3.8	3.0	0.9	1.3	1.2	0.1	4.8	4.4	0.4
variance	1.36	1.34	1.80	0.59	0.54	0.44	2.85	5.67	3.20
t_0			1.791			0.588			0.633
$t_{.05,7}$			1.895			1.895			1.895

Table 3. Flight control performance comparison chart

	speed goal			altitude goal			heading goal		
	w/GCM	w/o GCM	diff	w/GCM	w/o GCM	diff	w/GCM	w/o GCM	diff
mean	68%	64%	4%	43%	43%	0%	51%	48%	3%
variance	0%	1%	1%	0%	0%	0%	2%	1%	1%
t_0			1.287			0.045			1.219
$t_{.025,7}$			2.365			2.365			2.365

Therefore, it may be concluded that the use of GCM did not significantly affect pilot flight control performance during the simulation.

DISCUSSION

Overall, the laboratory experiments conducted for the present study demonstrated the ability of the GCM to successfully recognize overt and covert goals. Specifically, the overt and covert integrated method achieved at least 93% accuracy while the overt GCM alone obtained the average 91% accuracy after the first utterance and 99% accuracy after the second (corrective) utterance. It was also indicated that the GCM neither statistically imposed extra workload on the subjects, nor affected subjects' flight control performance.

However, this is not to say that the GCM would not face potential limitations when applied to real flight systems. Strictly speaking, the subjects' workload was slightly increased when using GCM in the experiment although the figures were not statistically significant. Furthermore, under the stressful conditions in a real flight system, the GCM may impose a significant additional workload. Nevertherless, if we accept the cost of the trials compared to the benefit of employing GCM which has been mentioned above, the GCM being considered can be used accurately as an embedded method to communicate pilots goals within the complex cockpit operations. And also the potential problems and limitations of the GCM used for this study may be significantly overcome by resolving the limitations in ASR technology and in intent inferencing.

Limitations to ASR Technology

Over the past two decades advances in ASR technology have contributed to a technology that has potential for aviation domains exhibiting mentally, physically and psychologically stressful environments. But, as seen from the experimental results, approximately 9% of GCM overt goal declarations were incorrect after the first utterance. This level of accuracy is not sufficient for real world applications. Nevertheless, several investigations have successfully used ASR systems for the recognition of overtly declared pilots goals in real cockpit environments, leading to the overall conclusion that most overt goal recognition errors could be removed by repeating declarations of unrecognized goals or by the application of updated ASR technologies (Williamson, 1996; Gerlish et al., 1995). In fact, the experimental results from the present study demonstrated that the second utterances for failed goal recognition achieved close to 100% accuracy. Thus, if we accept the costs of second trials or of the inclusion of advanced technologies, the GCM can be considered to be an accurate means of goal communication.

Limitations to Intent Inferencing

To resolve the workload associated with overt communications, the present study employed a model-based inferencer to infer pilot goals. Although the experimental results showed almost perfect recognition accuracy of the covert goals, the accuracy of the covert GCM probably resulted in large part from the fact that the inferencing was done in a highly simplified environment and was based on limited actions, simple scripts and rules, and simple scenarios. The effective use of intent inferencing in a more realistic environment would require a more robust intent inferencing mechanism such as the Georgia Tech crew-activity tracking system (GT-CATS) (Callantine and Mitchell, 1994). To infer the flightcrew goals, GT-CATS decomposes operator function into automatic control modes, which can be used to perform the functions. Each mode in turn decomposes into the tasks, subtasks, and actions required to use it, depending on the situation.

CONCLUSION

Insofar as it was demonstrated that the GCM developed for the present study has the capacity to recognize pilot goals with a high degree of accuracy and with little or no increase in workload, we conclude that GCM is suitable for use in the AgendaManager, at least for development purposes. To the extent that the use of the AMgr is restricted, for the time being at least, to laboratory or training environments, GCM should be a suitable front end' to correctly recognize pilot goals. Future implementations of the AMgr in real aircraft will require better automatic speech recognition systems and more robust intent inferencing mechanisms.

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