# A CLOSED-LOOP, ACT-R APPROACH TO MODELING APPROACH AND LANDING WITH AND WITHOUT SYNTHETIC VISION SYSTEM (SVS) TECHNOLOGY

Michael D. Byrne*, Alex Kirlik†, Michael D. Fleetwood*, David G. Huss*, Alex Kosorukoff†, Ruei-sung Lin†, Chris S. Fick*

*Department of Psychology, Rice University
Houston, TX
†Beckman Institute & Institute of Aviation, University of Illinois
Urbana, IL

We present a computational model of closed-loop, pilot-displays-aircraft system designed to evaluate the impact of the addition of a synthetic vision system (SVS) to a commercial airliner cockpit. The NASA-run empirical study revealed that while pilots rarely looked out the window during most phases of approach and landing, they devoted a substantial proportion of their gaze toward the SVS. A model pilot implemented in ACT-R was connected to a commercial flight simulator package in an attempt to model pilots' attention allocation behaviors. Based on metrics such as transitions from one display to another, the model provides a good approximation to pilot behaviors and should allow us to perform virtual experiments on the impact of changes to the SVS.

Evaluation of new technology for the commercial aircraft cockpit is an expensive and time-consuming process. The pool of potential subjects is small and consists of individuals with extensive training who are both relatively difficult and expensive to access. Thus, the typical design-test-modify iteration cycle is generally both slow and costly. One approach with potential application in this domain is the substitution of computational cognitive modeling for at least some phases of empirical evaluation. While we are not suggesting entirely removing humans from the evaluation process, other engineering disciplines rely heavily on mathematical or computational simulation models as a routine part of design. (This has been argued in more detail elsewhere; e.g., Byrne & Gray, 2003).

The focus of this research is on the evaluation of a new technology for the commercial airline cockpit (Foyle, et al., 2003). One of the factors that has long limited aviation is visibility; poor visibility conditions can substantially change the task of piloting an aircraft. However, with extensive and accurate computer-based geographic information systems, it is possible to generate the view of known terrain as long as the location of the observer is known. Modern GPS systems make it possible to know the location of an airplane with high accuracy. Thus, the combination of the two systems makes it possible to render on a computer display the terrain that may not be visible due to adverse environmental conditions (e.g. fog, rain). This is the basis for NASA's Synthetic Vision System or SVS. That is, an SVS is essentially a computer generated display designed to provide the pilot with information that augments the out-the-window view, to better enable the pilot to fly safely, at low levels, through traffic, around terrain, and in low visibility conditions. Experiments were performed to investigate the potential positive and negative effects of augmenting a cockpit with a prototype SVS display (Goodman, et al., 2003). A similar SVS is also under evaluation by standard field-trial methodology (Prinzel, et al., 2002); we see these two approaches as complimentary.

One of the original motivations in this research was to try to understand the impact of the SVS on errors made during approach and landing. Aviation incident and accident investigations often find both cognitive and environmental sources of human error. Environmental sources include factors such as flawed interface design, confusing automation, and unexpected weather conditions. On the other hand, cognitive sources underlying the effectiveness and efficiency of performance include factors such as situation awareness, procedural compliance or non-compliance, and crew coordination. Many if not most significant incidents and accidents result from some combination of both cognitive and environmental factors. Introducing new technology is a common approach to trying to reduce either the frequency, severity, or consequences of less-than-perfect pilot performance. Human performance modeling associated with evaluating the impact of technological interventions therefore requires giving consideration to both cognitive and environmental issues. This was a key lesson learned from work on a different task from the same domain, surface taxiing operations (Byrne & Kirlik, in press).

## METHODS AND RESULTS: EMPIRICAL STUDY

The empirical study, which was conducted at NASA Ames Research Center by NASA and Monterey Technologies Inc., is described in detail in Goodman, et. al (2003). Pilots were placed in a flight simulator which approximated the instruments and controls of a Boeing-757. The aircraft simulator was linked with a visual database modeling Santa Barbara Municipal Airport and its surrounding terrain. The purpose of these experiments was to collect data characterizing pilot performance and eye movement behavior during the approach and landing phase of flight using with both conventional and augmented displays under both Instrument Meteorological Conditions and Visual Meteorological Conditions.

The most striking result of the simulator study is that there was very little impact of the SVS on pilot performance in terms of errors or the quality of the observable decisions made by the pilots. We believe this is due to the fact that for a well-trained and highly-motivated commercial pilot, the approach and landing scenarios, flown primarily by the autopilot, were well within their competence.

However, there was one aspect of the pilots' behavior which was significantly impacted, which was their allocation of gaze across the various available displays. In the experimental configuration, there were multiple displays at which the pilot could look. These included looking out the window (OTW), the SVS, the primary flight display (PFD), the navigation display (NAV), the mode control panel (MCP) and a display for miscellaneous controls (DMC). Additionally, the scenarios flown by the pilots were divided into four phases. Phase 1 was from the scenario beginning to the first waypoint in the approach; Phase 2 was from the first waypoint through the last waypoint; Phase 3 was the last waypoint to the landing decision altitude; and Phase 4 was from the decision altitude through the end of the scenario. The longest phase, by a substantial margin, was Phase 2, as the approach required flying through several waypoints.

Not surprisingly, the distribution of the pilots' fixations on the various displays was a function of the phase of flight. The most interesting effects of the SVS were actually in the first two phases of flight. This may seem counter-intuitive, but the reason is that while pilots in the baseline (i.e., non-SVS) condition rarely looked out the window (less than 3% of the time was gaze directed there), approximately 20% of their gazes were directed at the SVS display. Thus, the SVS was *not* simply a proxy for looking out the window and the presence of this new display had a substantial impact on pilots' attention allocation. Figure 1 displays the proportion of the fixations which fell in each region ("off" meaning the equipment could not determine the location of the fixation for reasons such as blinking) for Phase 1, while Figure 2 presents the same information for Phase 2.

As is clear from the graphs, the pilots rarely looked out the window at all, yet when the SVS was present, they devoted a considerable proportion of their fixations to it.

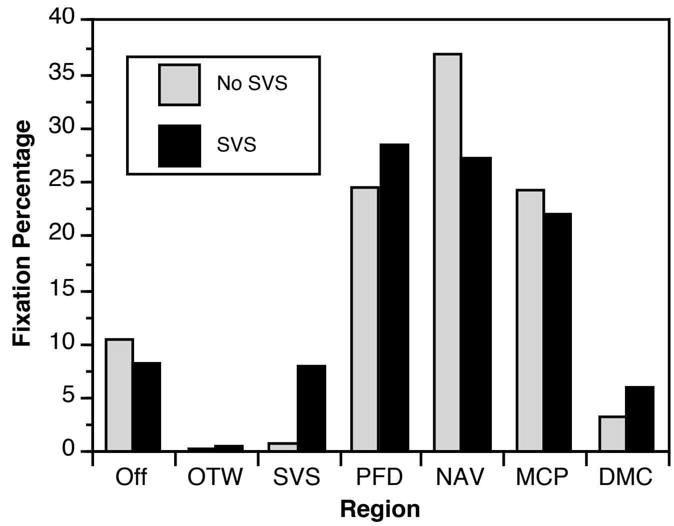


Figure 1. Percentage of fixations in each region, Phase 1

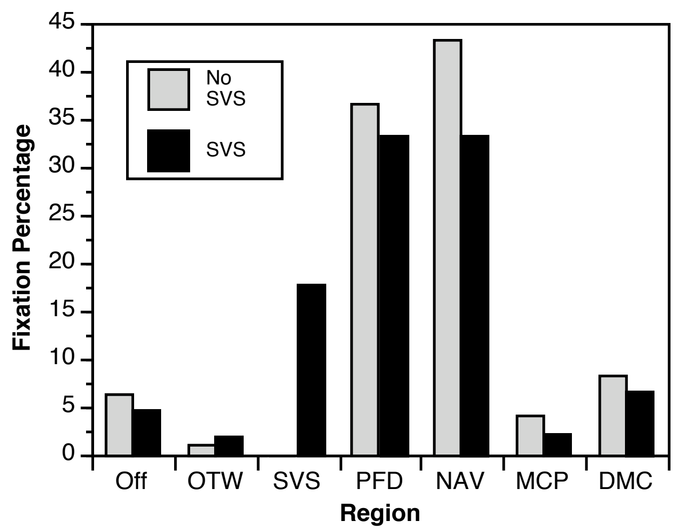


Figure 2. Percentage of fixations in each region, Phase 2

Another index of attention allocation is the pattern of transitions from one display to another. Table 1 presents the probability that a fixation on one display will be followed by a fixation on a particular display for Phase 2, without SVS. So, for example, the probability that a randomly-selected transition will be from the PDF to the NAV is 10%. Cells with < 1%

probability have been omitted. Table 2 presents the same data in the SVS condition. The key finding to note is that once attention is directed to a particular display, it tends to stay there; most fixations on a region are followed by another fixation on the same region.

Table 1. Human probability of transition from (vertical) one display to another (horizontal), Phase 2, no SVS

| | OTW | SVS | PFD | NAV | MCP | DMC |
|---|---|---|---|---|---|---|
| OTW | 0.02 | - | - | - | - | - |
| SVS | - | - | - | - | - | - |
| PFD | - | - | 0.25 | 0.10 | - | - |
| NAV | - | - | 0.10 | 0.27 | - | 0.01 |
| MCP | - | - | - | - | 0.04 | - |
| DMC | - | - | - | 0.01 | - | 0.05 |

Table 2. Human probability of transition from (vertical) one display to another (horizontal), Phase 2, SVS

| | OTW | SVS | PFD | NAV | MCP | DMC |
|---|---|---|---|---|---|---|
| OTW | 0.1 | - | - | - | - | - |
| SVS | - | 0.14 | 0.02 | 0.01 | - | - |
| PFD | - | 0.02 | 0.22 | 0.08 | - | - |
| NAV | - | 0.01 | 0.08 | 0.22 | - | - |
| MCP | - | - | - | - | 0.02 | - |
| DMC | - | - | - | - | - | 0.05 |

Again, it is clear that the SVS had a substantial impact on the pilots' allocation of attention during this phase of flight.

## METHODS AND RESULTS: COMPUTATIONAL COGNITIVE MODEL

We have constructed a model pilot using the most recent version of the ACT-R cognitive architecture, ACT-R 5.0 (Anderson, et al., in press). ACT-R is a computational cognitive architecture which takes as inputs knowledge about how to do the task, both procedural and declarative, and a simulated world or environment in which to run. It contains a variety of computational mechanisms and the ultimate output of the model is a time stamped series of behaviors including individual attention shifts and saccades, speech output, button presses, and the like.

One of the things which distinguishes an analysis at the level of a cognitive architecture such as ACT-R is that it is possible to "close the loop" of the human-machine system. That is, both the human and the evaluated system are modeled dynamically and in detail, and the two sub-models are coupled, yielding a model of the complete dynamic system. Work on the taxiing model revealed that fidelity of the machine/environment model was critical in understanding the performance of the human model; in particular, many of the "higher-level" decisions ultimately depended on "low-level" properties of the human-environment system.

For the aircraft model, we used the commercially-available flight simulator package X-Plane, which has been certified by the FAA for use in pilot training (see <http://www.x-plane.com/FTD.html>) for details. The simulator must be provided with the appropriate aircraft model (readily available) and an autopilot program, which we developed ourselves based on the approach plate provided by NASA. ACT-R is coupled to X-Plane via a low-level UDP network connection, as depicted in Figure 3.

The knowledge given to ACT-R to model the pilot was based on a detailed task analysis provided by NASA (Keller, Leiden, & Small, 2003) and interviews with a subject matter expert who is a captain and flight instructor for a major U.S. carrier. The primary point of comparison for the model output is the human eye-tracking data, which can be examined at various levels of abstraction.

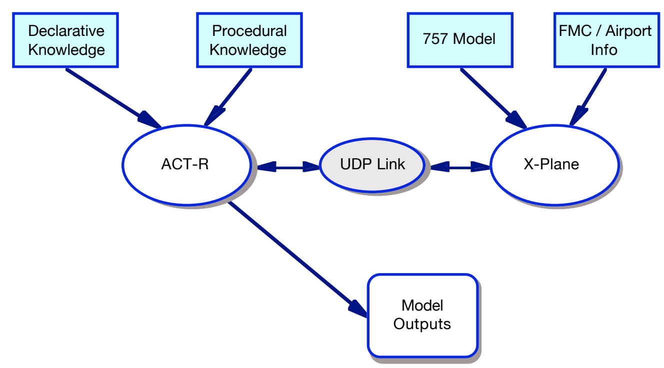


Figure 3. System overview

The first issue addressed by the model is why pilots rarely look out the window but allocate considerable attention to the SVS. The task analysis coupled with the model's memory dynamics indicated that as pilots update their internal representation of the flight, they require little information which is available out the window. However, the SVS displays more than that; it has symbology overlaid which displays many pieces of flight information (e.g., altitude, airspeed, heading) that are redundant with other displays. Thus, our model pilot looks at the SVS primarily as a proxy for other instruments, rather than as a proxy for OTW. This can be seen by looking at the model's performance in SVS vs. no SVS conditions in Phase 2, as presented in Figures 4 and 5. ("Off" fixations are omitted since the location of all model-generated fixations is determinable.)

While the model presently overestimates the proportion of fixations directed at the NAV display, we believe most of the mismatches in the are a result of inaccuracies in the knowledge given to the model and are in the process of revising the model based on further discussions with our SME. More importantly, the model does a good job of capturing the fixations which are drawn to the SVS when it is added to the cockpit environment.

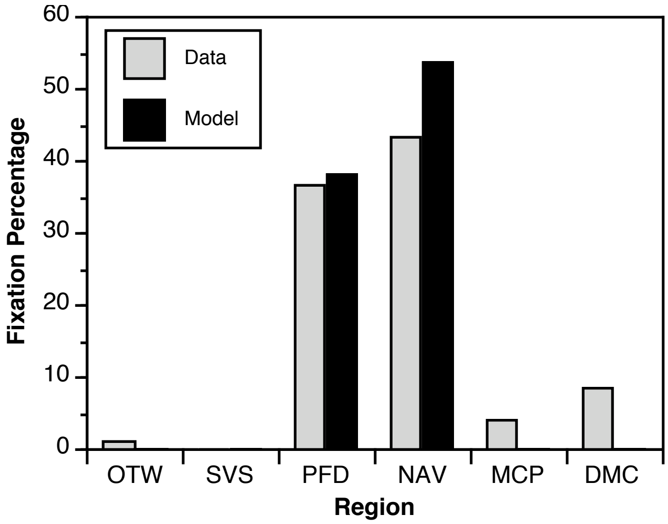


Figure 4. Model and data performance, Phase 2, no SVS

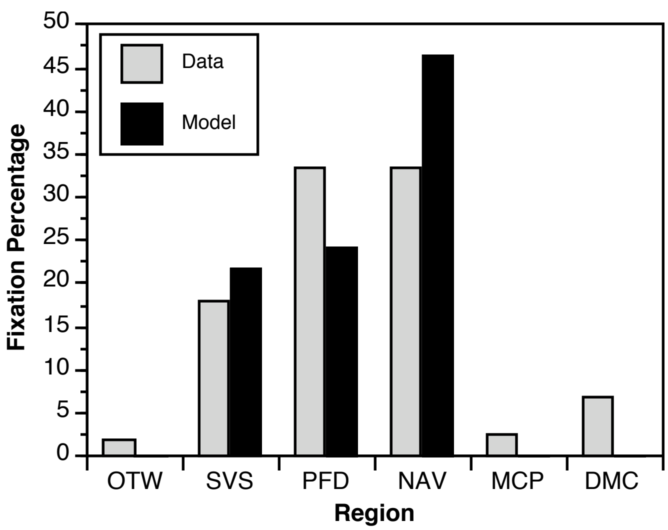


Figure 5. Model and data performance, Phase 2, with SVS

In addition, the model enables more fine-grained comparisons than simply that. A transition matrix like the one obtained from the experimental subjects is also generated by the model. Table 3 presents the matrix generated by one run of the model in Phase 2 without SVS, and Table 4 shows the SVS condition. Compare these with Tables 1 and 2, respectively.

While the model does not perfectly match the human data, the numbers are a promising approximation, r-squared of 0.80 when looking at both SVS and non-SVS conditions. And again, certain aspects of the knowledge given to the model are currently under refinement based on discussions with our SME, and we hope this will correct mismatches between the model and the data.

Table 3. Model probability of transition from (vertical) one display to another (horizontal), Phase 2, no SVS

| | OTW | SVS | PFD | NAV | MCP | DMC |
|---|---|---|---|---|---|---|
| **OTW** | - | - | - | - | - | - |
| **SVS** | - | - | - | - | - | - |
| **PFD** | - | - | 0.16 | 0.15 | - | 0.07 |
| **NAV** | - | - | 0.15 | 0.38 | - | - |
| **MCP** | - | - | - | - | - | - |
| **DMC** | - | - | 0.07 | - | - | 0.01 |

Table 4. Model probability of transition from (vertical) one display to another (horizontal), Phase 2, with SVS

| | OTW | SVS | PFD | NAV | MCP | DMC |
|---|---|---|---|---|---|---|
| **OTW** | - | - | - | - | - | - |
| **SVS** | - | 0.08 | 0.06 | 0.04 | - | 0.03 |
| **PFD** | - | 0.05 | 0.08 | 0.07 | - | 0.04 |
| **NAV** | - | 0.05 | 0.06 | 0.35 | - | - |
| **MCP** | - | - | - | - | - | - |
| **DMC** | - | 0.03 | 0.04 | - | - | 0.01 |

## DISCUSSION

Overall, the model indicates that the SVS stands in as a proxy not just for looking out the window, which was the original design intent, but due to the symbology overlaid on the SVS itself, also as a secondary instrument cluster. So, while the SVS made only a small difference in overall pilot performance in the particular scenarios evaluated in the NASA study, it had a dramatic impact on the pilots' allocation of attention across the various displays. While this did not have much impact on performance in the relatively easy scenarios faced by in this study, we believe this could potentially impact performance in other approach and landing scenarios.

Therefore, we intend to explore the impact of alterations in the SVS overlay symbology on the model's attention allocation to get a better indication of the impacts of specific symbology choices. For example, we can remove the heading indicator provided on the current SVS and assess how this changes the model's allocation behavior. Similarly, we can assess the impact of adding information (e.g. vertical deviation from the specified GPS flight path) to the SVS, since we have a "virtual SVS" with which the model can interact.

Based on informal examinations of the model's interaction with the system, we can already recommend two changes to the SVS. First, pilots' information needs change substantially during different phases of flight, and since the SVS is dynamic, it should be possible to condition the overlaid symbology based not only on the phase of flight, but on specific needs which arise at particular points within those phases (e.g., near waypoints). One additional recommendation is that the waypoints themselves be rendered as virtual objects on the SVS, since assessment of relationship to the next waypoint is a critical and oft-repeated task which could be better supported than it is on current displays.

There are other potential payoffs to this approach as well. There is nothing about the model which is intrinsically tied to the SVS. That is, the model could potentially be used to assess the impact on attention allocation of other changes in the cockpit, such as adding or removing other instrumentation, or making alterations to extant displays such as the PFD.

One a more theoretical level, we are also investigating the relationship between our relatively detailed low-level ACT-R model and more abstract models of attention allocation exemplified by Senders (1964) and Wickens (2002). We believe that these higher-level descriptions may be characterizations of behaviors which are emergent from the lower-level properties of the human visual-cognitive-motor system, as instantiated in models like ACT-R. This may useful in determining parameter values and boundary conditions for such higher-level models, many of which are currently set in useful but not necessarily principled ways.

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