Automating Hand Signal Recognition: Transforming Helicopter Signaling Skills Training

John W. Ruffner, Ph.D., Dmitry E. Shiraev, Peter A. Morey, Jim E. Fulbrook, Ph.D.,
Andrew D. Struckhoff, DCS Corporation, Alexandria, VA
Thomas M. Franz, Psy.D., NAVAIR - Orlando Training Systems Division, Orlando, FL

Abstract

In 2006 the United States Navy will acquire four new Vertical Flight Deck Training Systems (VFDTS) that combine virtual reality simulation of helicopter shipboard landings, takeoffs, and over-deck operations with an automated Hand Signal Recognition System (HSRS), effectively transforming how and where initial helicopter signaling skill acquisition and refresher training before or between deployments can be conducted. In this paper, we describe the development and evaluation of the HSRS and discuss training issues and challenges faced by the project team. We identify instructional design issues and suggest some future HSRS capabilities and applications. Finally, we discuss links to the Department of Defense Training Transformation Initiative.

ABOUT THE AUTHORS

Dr. John W. Ruffner is a Human Factors Engineering Psychologist and a Board Certified Human Factors Professional with DCS Corporation where he is a Senior Scientist and Technical Advisor for Human Factors and Training. He received a Ph.D. in Industrial/Organizational Psychology and an M.S. in Experimental Psychology from Iowa State University. He has over 30 years experience in human factors research and development and test and evaluation (RDT&E) in training development, night vision systems, and human system integration for a wide variety of aviation and ground systems. He has over 100 publications, conference proceedings papers, presentations, and reports.

Dmitry E. Shiraev is a Computer Scientist supporting design, development, and integration of software systems at DCS Corporation. He has an M.S. in Computer Science and Applications and B.S. degrees in Computer Science and Mathematics from Virginia Tech. Mr. Shiraev is currently providing software engineering support for the Hand Signal Recognition System project

Peter A. Morey is a Systems Engineer for the Electro-Optical Design and Engineering Branch at DCS Corporation. He has a B.S. in Imaging Science, with a minor in Electro-Optics (E-O), from Rochester Institute of Technology. Mr. Morey’s professional specialties are in optics, digital image processing, and software development. He is the lead E-O engineer for the Hand Signal Recognition System project.

Andrew D. Struckhoff is a Systems Engineer and Technical Advisor in the Electro-Optical Design and Engineering Branch at DCS Corporation. He has 15 years experience in the development, analysis, test and operation of machine/computer vision systems, E-O systems, E-O calibration, software design and development, and real-time image processing algorithms.

Dr. Jim E. Fulbrook is a Human Factors Engineer with DCS Corporation. He received a Ph.D. in Neurobiology and an M.S. degree with specializations in vision research and learning theory from the University of Delaware. He has over 25 years experience in research psychology and human factors and is a former Army helicopter pilot and flight instructor. He has published over 30 papers and reports.

Dr. Thomas M. Franz is an Industrial/Organizational Psychologist working as a civilian for the last 15 years at the United States Navy's NAVAIR Orlando Training Systems Division. Prior to that he served a pre-Doctoral Internship at IBM’s Management Development Center in Armonk, NY, and a post-Doctoral Fellowship with the Navy. Dr. Franz teaches evenings and on-line for Columbia College of Missouri. His degrees are from Central Michigan University.

Automating Hand Signal Recognition: Transforming Helicopter Signaling Skills Training

John W. Ruffner, Ph.D., Dmitry E. Shiraev, Peter A. Morey, Jim E. Fulbrook, Ph.D.,
Andrew D. Struckhoff, DCS Corporation, Alexandria, VA
Thomas M. Franz, Psy.D., NAVAIR - Orlando Training Systems Division, Orlando, FL

INTRODUCTION

A critical problem facing the services is the decline of skills and readiness that occurs between initial training and initial assignment, and between deployment periods. Major challenges in addressing this problem are to provide training to personnel when proficiency levels declines and to economize the demand on and need for subject matter instructors.

A performance domain in which training progression and sustainment issues are particularly relevant is the signaling and control of helicopters aboard Navy ships by Landing Signal Enlisted (LSE) crewmembers. NAVAIR Orlando Training Systems Division (TSD) is sponsoring research to develop a Vertical Flight Deck Training System (VFDTS) that combines virtual reality (VR) simulation of helicopter shipboard landings, takeoffs, and over-deck operations (Holmes, Franz, Struckhoff, and Salva, 2004) with an automated Hand Signal Recognition System (HSRS) (Ruffner, Fulbrook, Struckhoff, Morey, and Franz, 2004). The VFDTS was designed for initial skill acquisition at the schoolhouse, and for refresher training before or between deployments. In this paper we describe the development and evaluation of the HSRS, an automated system for recognizing LSE hand signals and interfacing with the VFDTS, and discuss its links to the Department of Defense (DoD) Training Transformation Initiative.

SHIPBOARD HELICOPTER SIGNALING

Shipboard Helicopter Operations

Conducting helicopter operations on Navy ships requires a high degree of coordination and communication among pilots, crew chiefs, and shipboard personnel to safely land and launch aircraft (see Ruffner, Padukiewicz, and Meier, 2002; 2003). A key shipboard person is the LSE who is responsible for visually assisting the pilot with the proper handling of the helicopter for safe deck operations (see Figure 1).

Figure 1. LSE signaling a helicopter aboard ship. The LSE standing in front of the helicopter in the center of the picture is giving the Hover signal.

The LSE watches in all directions for other traffic, directs the pilot to the desired deck spot, and also ensures safe operations at the flight deck area. In particular, the LSE must observe the aircraft carefully for any sign of malfunction (such as smoke, oil, or hydraulic leaks), or an unsafe condition (such as other aircraft nearby, personnel on deck, landing gear not lowered), and respond in the appropriate manner. The LSE ensures that the helicopter is started, launched, recovered, and shut down safely, and uses hand signals to communicate with the helicopter aircrew. The signals are advisory in nature, with the exception of mandatory Wave Off and Hold signals used when an emergency condition exists or when an unsafe situation arises. LSE tasks also include supervision and control of the flight deck crew (Department of the Navy, 1998a).

LSE Training

LSE formal training has consisted of classroom instruction and practical exercises at the schoolhouse. Previously, the students collectively received a one-hour class on basic helicopter signals and two two-hour live helicopter practice periods. The live practice periods are conditional on favorable weather and the availability of a helicopter. During each of the two supervised practice periods, each student typically receives only two minutes of supervised live daytime interaction with a helicopter (Figure 2). Additional detail about LSE training, including newly developed computer/web-based training, is provided in Ruffner, Titley, Fulbrook, and Franz (2004).

Figure 2. Supervised LSE signaling training during a live practice pad session. The student (left) is giving the "Move Right" signal under instructor supervision.

Helicopter Signaling Simulation Training

Because of a lack of live helicopter signaling training opportunities, the Navy identified a need for, and will be acquiring in 2006, four new Vertical Flight Deck Training Systems (VFDTS). The purpose of the VFDTS is to transform the training of Navy LSEs on basic signaling skills during schoolhouse training by using VR simulation of a helicopter that automatically responds to LSE hand signals or to an instructor/operator's manual interventions. Carmel Applied Technologies, Inc. (now ALION/CATI) developed the VFDTS for the Navy as part of a NAVAIR – Orlando Phase II SBIR project (see Holmes, Franz, Struckhoff, and Salva, 2004). DCS Corporation was tasked to develop the HSRS as part of that project.

HAND SIGNAL RECOGNITION SYSTEM

The HSRS applies computer vision and image processing technologies to recognize a subset of trainee hand signals without instructor intervention, and to cue appropriate responses of the simulated helicopter. The HSRS applies techniques used in sign language recognition research, and overcomes many shortcomings of previous motion recognition systems, as discussed below.

A detailed description of the HSRS is beyond the scope of this paper, and will be contained in the project final report (Struckhoff, Morey, and Shiraev, 2005). Rather, our intention in this section is to provide the reader with sufficient background information to obtain a basic understanding of the HSRS and an appreciation for some of the technical engineering challenges encountered and design decisions made during system development, especially those made in support of achieving overall training system goals.

Design Considerations

To meet the project requirements, it was necessary to develop a system to recognize LSE arm and hand signals automatically (i.e., without instructor intervention), and use this information to trigger VR simulation training scenarios depicting helicopter maneuvers and events in response to the correctness or incorrectness of the signals. We first investigated commercial off-the-shelf (COTS) systems capable of tracking hand and arm motion. Systems are available in wired or wireless versions, which would enable a student to move about, tethered or untethered, in a limited area.

There are several factors that limit the ability of these types of systems to meet the project requirements and cost constraints. First, both the wired and wireless versions required that the student be suited with sensors, which would not be practical for either the schoolhouse or shipboard applications. In addition, the performance of some types of student-mounted components is degraded by metal objects and stray magnetic fields. This would prohibit the system being used reliably in heavy metal spaces, such as on board ship. Similar problems were found with acoustic and optical sensors as well. Another negative factor is the high system cost, depending on the number of sensors needed. Therefore, we decided that COTS hand/arm motion trackers were not suitable for the project, because of (1) high system cost, (2) the requirement to attach sensors and, (3) in the wired configuration, to tether the sensors worn by the student to a transmitter.

We observed that there is a great deal of similarity of how American Sign Language (ASL) signs and LSE hand/arm signals are made. As an example, Figure 3 illustrates the physical similarities between the ASL sign and the NATO-approved hand signal for "Land." Therefore, we considered it appropriate to investigate ASL automatic sign recognition techniques for lessons we could apply to this project Traditionally, research on gesture and sign language recognition has typically used (1) expensive data gloves or body suits which, at least in the wired versions, tether the user to a stationary machine, or (2) more conventional computer vision systems that restrict the user to a calibrated area and require an unrestricted line of sight. ASL researchers found that, given certain constraints (e.g., viewing a person against a simple, unchanging background, no occlusions of the hands), a relatively high level of sign recognition accuracy (i.e., 80-90%) is possible with a computer vision system supplemented by statistical techniques. In addition, these researchers found that color coding body components helps to increase system robustness and recognition accuracy (see Starner and Pentland, 1995).

Figure 3. Comparison of "Land" signal for ASL (left) and NATO-approved hand signal (right).

The initial concept for the HSRS involved using a single black and white COTS camera to track and record LSE hand signals and image processing software to track and recognize the hand signals in real time. The trainee had to wear a short sleeve solid dark shirt or vest that provided sufficient brightness contrast between the trunk of the body and the arms, hands, and face. This was necessary so a brightness threshold can be determined that segments the hand/arm area as an area of uniform brightness, or "blob" in computer-vision terminology. A *blob* is defined as a connected group of pixels in either the foreground or background region. The same thing is done for the face area. A blob analysis consists of analyzing parameters of the blob (i.e., size, length, width, angle of major axis) and then assigning meaning to the results (see Starner, Weaver, and Pentland, 1998).

A restriction of the initial prototype was that there could be no movement in the background of the camera field of view, apart from the trainee doing the signaling. This was necessary for the system to "register" the unchanging stationary scene elements for comparison to the moving elements. In addition, lighting that is typical of a work area or classroom must be provided, and should be uniformly distributed. In general terms, the initial prototype HSRS worked by detecting the angle formed by the hand/arm image or blob. It classified the trainee's hand/arm position as one of the LSE hand signals using an algorithm that interprets the hand/arm angle according to a pre-defined set of rules (see Figure 4).

HSRS Prototype Characteristics

The operational concept for the HSRS was that it would be deployed in a classroom with the LSE facing the camera in front and the students observing the LSE's actions from the back. As such, the students would be in the field of view of the camera. Thus the system had to track the motion of the LSE performing the signals and filter out the motion that is part of the background. In addition, different LSE students would have different physical characteristics, such as height and build. Therefore, the system had to be robust enough to recognize hand signals regardless of the particular geometric properties of the LSE student.

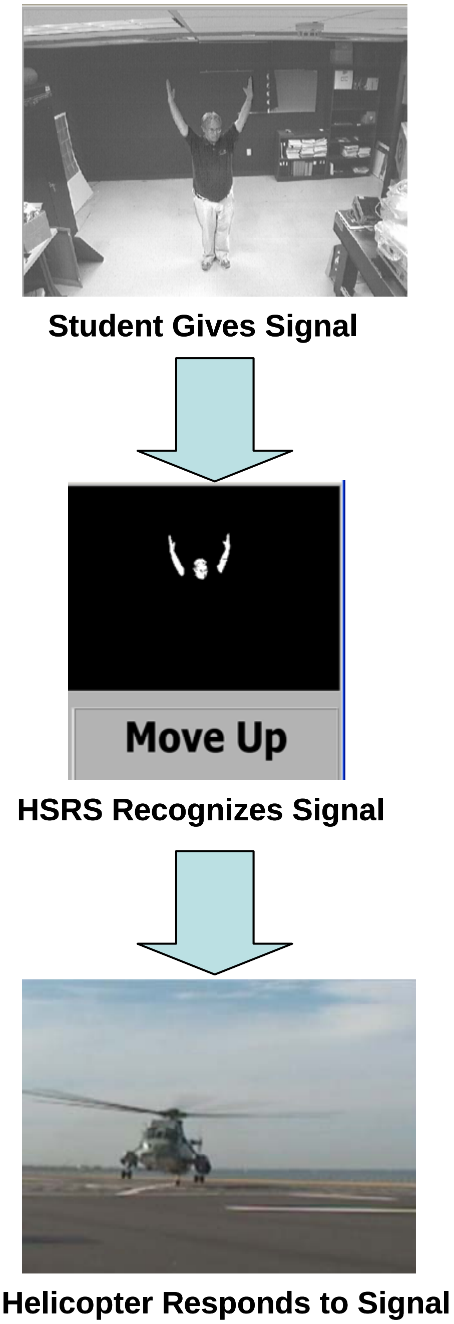

Figure 4. Generic hand signal recognition process.

Hand Signals Recognized

Table 1 lists the subset of signals that are recognized by the final prototype HSRS. The HSRS was designed to recognize both static and dynamic signals (i.e., involving hand/arm movement). An example of a static signal is the Hover signal shown in Figure 1, and an example of a dynamic signal is the Move Right Signal shown in Figure 2. The interested reader should consult the Navy *Aircraft Signals NATOPS Manual* (Department of the Navy, 1998b) for graphic illustrations of these signals and hand/arm movements.

Table 1. Signals Recognized by the HSRS

Static	Dynamic
I Have Command	Move Left
Hold Position	Move Right
Hover	Move Up
Affirmative	Move Down
Negative	Take Off
This Way	Wave Off
Land	Move Ahead
	Move Back
	Swing Tail Left
	Swing Tail Right

Image Processing Approaches

As noted previously, one of the major challenges the design team had to overcome was variable light level conditions. There are several image-processing approaches that could be applied to this problem. We focused on a small number of approaches before arriving at a solution.

Component Tracking

We determined that in order to recognize the required hand signals, we had to track only three different parts of the body: the hands, elbows, and chest. As such, our system had to separate the required components from a dynamic background and track them between sequential image frames. We determined that the best way to do this was to use a color coding approach to identify critical body components, and to then interpret hand signals by considering the relation of the components (see Starner and Pentland, 1995).

Body Geometry

Once we identified the body components we wished to track and had their blob characteristics, we developed a system of geometric relationships between them. We determined the approximate position of the shoulders and determined the angles between the shoulders, elbows, and hands. Using angles allowed us to ignore many anthropometric attributes that vary among people, such as arm length.

Pattern Recognition

After completion of the image processing, we had a variety of information about the body components as well as geometric information about how these components form the image of a person. This information included an interpretation for which hands and elbows form the right and left arms, and the angles between the shoulders, elbows, and hands. At this point, the challenge was to determine how the changes in these attributes over time could be identified as particular signals.

There are four primary models for pattern recognition: (1) template matching, (2) statistical, (3) syntactical (structural), and (4) neural networks (Jalin, Duin, Mao, 2000). Work has been done in gesture recognition using Hidden Markov Models (Starner and Pentland, 1995), which fall under the statistical category for pattern matching. The drawback to statistics-based pattern recognition is that there needs to be a significant data set for creating the probabilistic models. In our case, the data set would need to be an extensive library of hand signals being performed by trained LSEs. The individuals that performed the signals would have to be of sufficiently varying physical dimensions, and they must perform the correct signals consistently.

In reality, we had only a limited number of LSE instructors to work with, and we discovered that there were variations in interpretations about how to perform the signals. Therefore, there was no possibility of creating an adequate data set for training statistical models or neural networks, or for creating adequate templates for a template matching approach.

Accordingly, we decided that the solution lent itself better to breaking down signals into basic or “primitive” components (e. g, a straight arm pointed upward), and then defining the signals as sequences of primitives (see Vogler and Metaxas [1998] for an example of a similar technique). Signal primitives are usually derived from the detected body geometry, which is derived from the detected body components. Our challenge then was to detect the correct sequence of primitives in a given period of time.

Tracking the LSE

The LSE student was expected to be able to move within about a 10-foot square area in front of the camera. Considering the space restriction in the classroom training environment, we had to place the student very close to the camera and as such, the movement area was larger than the field of view of the camera. We solved this problem by utilizing a pan-tilt camera unit that tracked the LSE student as they moved around in the 10-foot square area.

Integration with the VFDTS

The HSRS was designed to work with the VFDTS and as such, we passed the detected signals to the VFDTS computers. The HSRS and the VFDTS computers were connected by a local area network. During integration it was found that there was a significant lag between when the HSRS detected a hand signal and when the virtual helicopter would move according to the signal. This problem was addressed by both sides (i.e., HSRS and VFDTS) by having the HSRS send signals at a faster rate and having the VFDTS increase the speed at which the helicopter responded to a signal as it was detected. Figure 5 shows an example of a screen shot from the VFDTS (Holmes, Franz, Struckhoff, and Salva, 2004).

Figure 5. Screen shot from the VFDTS. The LSE is giving the Hover signal.

FLEET EVALUATION

During February 2005, LSE instructors at HC-8 Helicopter Operations School, NAS Norfolk, VA, conducted a signaling lab in which two classes of students were trained on the VFDTS/HSRS. Following the lab exercise, thirty-six students completed evaluation forms that contained items about the effectiveness of the HSRS. In general, the students were very positive about using the HSRS as part of the VFDTS helicopter simulation system. The greater majority (over 80%) of the students rated the HSRS as “Effective” or better. Instructor comments were likewise very positive.

Only one student judged that the HSRS was ineffective. The students commented on the HSRS characteristics, such as how “touchy,” “picky,” or “precise” it was for recognizing signals. In general, the students liked the combined VFDTS/HSRS helicopter signaling simulation training system and judged that it helped prepare them to benefit more from their next opportunity to practice signaling with an operational helicopter. Students also offered constructive suggestions for improving the instructional value of both the VFDTS and the HSRS.

INSTRUCTIONAL DESIGN ISSUES

The HSRS, as a functional adjunct to the VFTDS, affords many possibilities for implementing effective training concepts and instructional strategies for LSE signaling training. In the following paragraphs, we briefly discuss some applicable training concepts and instructional strategies.

Objective-Based Training

We suggest that the most beneficial application of the VFDTS/HSRS integrated system is one that focuses on objective-based learning. Specifically, trainees should be (1) provided clear learning objectives, (2) shown examples of specific helicopter maneuvers, (3) given directed practice on performing hand signals in response to different situations, (4) assessed on critical performance parameters, and (5) provided timely and constructive feedback.

For example, when a helicopter is shown approaching a ship at sea with excessive speed, a reasonable learning objective would be, “The student properly detects the excessive speed and waves off an approaching helicopter before it reaches the perimeter of the deck.” Variations of safe approaches can be recorded for presentation to demonstrate the acceptable tolerances and variations from “normal.” This could be followed by examples of various dangerous approaches to which the trainee must respond, pointing out critical visual cues for hazard detection and decision-making.

Standardization of Hand Signals

A lack of standardization in the performance of hand signals was noted as a deficiency during the recent development of a computer-based/web-based LSE trainer (Ruffner, Titley, Fulbrook, and Franz, 2004). Certainly an important use of HSRS would be as a standardization tool. The HSRS helps to standardize signaling performance because it requires students to perform the signals one way, regardless of school or individual instructor preferences.

Instructor Intervention

The VFDTS/HSRS gives the instructors the capability to introduce scenario variations during the training period. We envision two modes of instructor intervention. In the

Automatic Mode, the system automatically reacts to the LSE trainee's hand signals and presents a VR scenario accordingly. The onset of the scenario can be determined by branching logic established prior to the initial scenario. In the *Manual Mode*, the instructor can manually control the helicopter scenario, as well as controlling various scenario elements such as other aircraft traffic, or can intervene at timely opportunities to make a specific teaching point (e.g., keeping the arms straight, checking for aircraft traffic in the surrounding area).

Feedback

The VFDTS/HSRS design allows for automated student performance recording and playback capability. Accordingly, a useful instructional strategy would be to provide real-time feedback to the student trainee while the trainee is practicing the signals using picture-in-picture video inserts. This strategy is illustrated in Figure 6 which shows the visual scene presented to the trainee with two types of picture-in-picture video inserts: (1) a dynamic (i.e. moving), real-time depiction of the trainee's actual signaling performance (left), and (2) a dynamic depiction of the correct way to give the signal (right).

Figure 6. Illustration of trainee feedback concept.

FUTURE RESEARCH AND APPLICATIONS

In the process of developing the HSRS and interacting with LSE instructors, students, and NAVAIR, we identified several future capabilities and applications.

HSRS "Lite" – A Portable Ship-Board Trainer

The current HSRS is designed to be deployed in a classroom setting using a desktop PC computer and a high-end camera and capture board. The Navy funded a project to use the HSRS as a stand-alone system that could be deployed aboard ships to facilitate training of LSEs outside of the classroom setting. This would require the HSRS to be converted to a portable system using a laptop computer with lower processing capacity and a lower quality camera.

The system will need to function in more variable light level conditions with less control of the background colors. The current light-level normalization technique provides adequate performance for classrooms, but perhaps not for the ship environment. Further research and development is necessary to improve light-level normalization and optimize the image processing and pattern matching algorithms to work on a lower processing capacity system.

HSRS for Unmanned Aerial Vehicles

An area that could benefit from automatic hand signal recognition, as enabled by the HSRS, is the signaling and control of UAVs. Unmanned Aerial Vehicles (UAVs) have become a crucial component of the modern US defense strategy and will operate in diverse environments, such as from fixed bases and on ships at sea. Potentially, the HSRS pattern matching system can be used by a UAV to recognize hand signals. A new system for detecting body components would need to be considered due to the color restrictions on the uniforms of the individuals directing UAV traffic. Processing power would be further limited by a likely lower capacity onboard computer. More difficult challenges are coping with UAV speed and ability to find and stay on image to respond to its signal, and the dynamics of ship movement

Training Transformation

According to the DoD Training Transformation Implementation Plan, embedded training is to be designed, fielded, and integrated to support distributed live, virtual, and constructive connectivity. A key concept of this plan is that deployed forces must have the ability to sustain readiness through training and rehearsal, regardless of location or length of deployment (Department of Defense, 2004). However, sustaining readiness through training and rehearsal puts more demands on instructors. These demands can be mitigated by using enhanced training capabilities such as those described in this paper.

The HSRS, as part of an integrated VR simulation training system, can improve the effectiveness of training and simulation systems in several ways: (1) providing guidance about task execution to novice trainees without the aid of an instructor; (2) functioning as a "virtual" mentor or coach during training scenarios; (3) monitoring, recording, and evaluating trainee performance; and (4) delivering adaptive training and performance feedback tailored to the specific trainee needs. Accordingly, future research and development work should focus on refining the capabilities of the VFDTS and HSRS to further support the transformation of LSE training, especially with respect to leveraging instructional technology.

CONCLUSION

We developed and demonstrated a technique for transforming helicopter signaling skills training by automating hand signal recognition. Achieving the goals of Training Transformation requires the coordinated efforts of individuals from many diverse professional specialties. This project is an example of the successful use of the systems engineering approach to the design of an effective training system. This effort demonstrated how a multidisciplinary team of scientists, engineers, and training specialists can coordinate their efforts for the systematic and thoughtful application of technology to improve training effectiveness and promote Training Transformation.

ACKNOWLEDGEMENTS

This research was conducted under Navy Contract N61339-02-C-0153 for the NAVAIR - Orlando Training Systems Division. Dr. Thomas M. Franz was the Contracting Officer's Technical Representative. The authors wish to acknowledge the support of the Helicopter Operations Squadrons HC-8, NAS Norfolk, VA, and HC-3, NAS North Island, CA.

REFERENCES

Department of Defense. (2004). DoD *Training Transformation Implementation Plan*. Washington, DC: Department of Defense.

Department of the Navy. (1998a*). Helicopter operating procedures for air-capable ships*. (NWP 3-04-1). Washington, DC: Department of the Navy.

Department of the Navy. (1998b). *Aircraft Signals NATOPS Manual*. Washington, DC: Department of the Navy.

Holmes, B. J., Franz, T. M., Struckhoff, A. D., & Salva, M. (2004). *Vertical Flight Deck Training System*. Paper presented at the Image 2004 Conference Scottsdale Arizona, July 12-16, 2004.

Jalin, A. K., Duin, R. P., & Mao, J. (2000). Statistical pattern recognition : A review. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 22, No. 1, Jan 2000.

Ruffner, J. W., Padukiewicz, J. E., & Meier, J. D. Jr., (2002). Joint shipboard helicopter operations: Human factors issues and challenges. *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 46-50). Santa Monica, CA: Human Factors and Ergonomics Society.

Ruffner, J. W., Titley, K. D., Fulbrook, J. E., & Franz, T. M. (2004). Integrating technologies for shipboard helicopter signaling skill training. *Proceedings of the Interservice/Industry Training, Simulation and Education Conference* (pp. 223-234). Orlando FL: December 6 - 9 2004.

Ruffner, J. W., Fulbrook, J. E., Struckhoff, A. D., Morey, P. M., & Franz, T. M. (2004). What comes down must go up: Training shipboard helicopter signaling skills. *Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society* (pp. 2548-2552). Santa Monica, CA: Human Factors and Ergonomics Society.

Ruffner, J. W., Padukiewicz, J. E., & Meier, J. D. Jr. (2003). Human systems integration issues in joint shipboard-helicopter operations. *Proceedings of the Human Systems Integration Symposium: Enhancing Human Performance in Naval & Joint Environments*, Vienna, VA: June 23 – 25, 2003.

Starner, T., & Pentland, A. (1995). *Real-time American Sign Language recognition from video using Hidden Markov Models.* Technical Report 375. Cambridge, MA: MIT Media Lab.

Starner, T. Weaver, J., and Pentland, A. (1998). *Real-time American Sign Language recognition using desktop and wearable computer based video.* Technical Report 466, Perceptual Computing, MIT Media Laboratory, July 1998.

Struckhoff, A. D., Morey, P. A., & Shiraev, D. E. (2005, In Preparation). *Hand Signal Recognition System Phase II SBIR – Final Report (*Draft). Alexandria, VA: DCS Corporation.

Vogler, C., & Metaxas, D. (1998). ASL recognition based on a coupling between HMMs and 3D motion analysis. *Proceedings of the International Conference on Computer Vision* (pp. 363-369). Mumbai, India, January 4-7, 1998.