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A Flight Training Simulator For Instructing the Helicopter Autorotation Maneuver (Enhanced Version)

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14. ABSTRACT

Autorotation is a maneuver that permits a safe helicopter landing when the engine loses power. A catastrophe may occur if the pilot's control inputs are incorrect, insufficient, excessive, or poorly timed. Due to the danger involved, full-touchdown autorotations are very rarely practiced. Because in-flight autorotation training is risky, time-consuming, and expensive, the objective of the project was to develop the first helicopter flight simulator expressly designed to train students in this critical maneuver. A central feature of the project was the inclusion of an enhanced version of the Pilot-Rotorcraft Intelligent Symbology Management Simulator (PRISMS), a virtual-reality system developed by Anacapa Sciences and ThoughtWave. A task analysis was performed to identify the procedural steps in the autorotation, to inventory the information needed to support student task performance, to identify typical errors, and to structure the simulator's practice environment. The system provides immediate knowledge of results, extensive practice of perceptual-motor skills, part-task training, and augmented cueing in a realistic cockpit environment. Additional work, described in this report, extended the capabilities of the simulator in three areas: 1. Incorporation of visual training aids to assist the student in learning the proper appearance of the visual scene when the maneuver is being properly performed; 2. Introduction of the requirement to land at a particular spot, as opposed to the wide, flat open field initially used, and development of appropriate metrics of success; and 3. Inclusion of wind speed and wind direction settings (and random variability settings) to add a more realistic challenge in "hitting the spot."

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Contents

Page

Section 1. Project Background 1
Organization of the Report 1
Training and Accident Rate Reduction 1
Helicopter Accidents and the Autorotation Problem 2
What is Autorotation and How is it Performed? 3
Limitations of Typical Autorotation Training 4
The Potential for Simulator Training of Autorotation 5
Employment of the PRISMS Simulator 7

Section 2. Task Analysis and Typical Error Inventory 9
The Autorotation Task Analysis 9
Phase 1: Autorotation entry 10
Phase 2: Steady-state descent 11
Phase 3: Deceleration and touchdown 12
The Autorotation Error Inventory 13

Section 3. Training, Learning, and Instructional Analyses
Hierarchical Training Analysis 17
Learning Analysis and Instructional Analysis 18
Key Training Strategies for Autorotation Training 19
Instructional Support Features (ISFs) 24
ISF Matrix 26

Section 4. Definition of Simulator Requirements 29
Simulator Fidelity Requirements 29
Characteristics to Support Training Strategies and Techniques 32
Performance Measurement Capabilities 39

Section 5. Implementation of Autorotation Training in PRISMS 43
The Simulator Flight Model 43
Helicopter Dynamics Parameters 44
Aircraft, Cockpit, Displays, and Controls 45
Operational Environment 47
Experimental Control and Monitoring 48
Subject Control of Training Sessions 52

Section 6. Basic Instructional Sequence 55
Review of the Full-Down Autorotation 55
Initial Introduction to the PRISMS Simulator 55
Beginning the Training Sessions 56
Training Session Stage Linking 56

Contents (Continued)

Page

Employment of Basic Instructional Support Features....56
Employment of Advanced Features: Initial Condition Sets....57

Section 7. Suggestions for System Evaluation....59
Cost-Benefit Analysis of the PRISMS Autorotation Trainer....59
The Problems of Evaluating Flight Training Devices by Experiments and Ratings....60
A Proposed Approach for PRISMS Autorotation Trainer Evaluation....63

References....65

List of Figures

Figure		Page
1	Simplified illustration of the autorotation maneuver	3
2	The PRISMS simulator being flown by an expert pilot	8
3	The F-poles and flight path predictor used by Lintern et al	21
4	The symbolic display used by Lintern et al.	22
5	The abstracted simulator airspeed and rotor rpm indicators	30
6	Scene with a high density of pine trees on textured terrain	32
7	The landing field currently used in the autorotation trainer	33
8	Results feedback for immediate control sequence performance	33
9	The F-poles augmented visual aid for glideslope visualization	35
10	Appearance of the flight path marker symbol and example of the symbol changing size as the potential impact point nears the aircraft	36
11	Appearance of the flight path marker symbol and the landing spot indicator in the autorotation trainer field of view during the flare	37
12	Helicopter dynamics object attributes	44
13	Robinson R-22 exterior model	46
14	R-22 cockpit view from the initial position	46
15	Control and status screen	48
16	Chase view of the helicopter from the observer viewer	50
17	Immediate control sequence metrics	50
18	Glide metrics	51
19	Flare metrics	51
20	Touchdown metrics	51
21	Overall metrics	52
22	Excerpt from subject recording file	53

List of Tables

Table **Page**

1 Simulator Instructional Support Features and Training Strategies Potentially Applicable to Terminal Behaviors and Skills 28

2 R22 Flight Hour Costs 60

Section 1. Project Background

The helicopter autorotation maneuver is employed when engine power is lost to permit a safe, soft landing. Unfortunately, practicing autorotation in the aircraft is expensive and potentially dangerous. Thus, the need for a helicopter autorotation training simulator has become apparent. This report describes flight simulator software previously delivered to the Government and described in the report accompanying the software (Rogers & Asbury, 1999b) as well as several subsequent improvements to that software which extend the training capabilities of the simulator.

The original system has already provided immediate knowledge of results, extensive practice of perceptual-motor skills, part-task training, and augmented cueing in a realistic cockpit environment. New additions to the system include:

1. Incorporation of new visual training aids to assist the student in learning the proper appearance of the visual scene when the maneuver is being properly performed;
2. Introduction of a requirement to land at a particular spot, as opposed to the wide, flat open field previously used, and provision for appropriate metrics of success; and
3. Inclusion of wind speed and wind direction settings (with selectable random variability) to add a more realistic challenge in "hitting the spot."

Organization of the Report

For readers unfamiliar with helicopter autorotation and its training, this introductory section describes accident rates, conduct of the autorotation maneuver, limitations in current training, and the potential applications of the simulator system for autorotation training. Section 2 describes the autorotation task analysis and inventory of important performance errors. Section 3 discusses the training, learning, and instructional analyses employed in trainer development. Section 4 defines the specific simulator performance requirements. Section 5 presents the methods of implementing the simulator performance requirements in the PRISMS simulator and the human-computer dialogue employed in setting up and conducting training sessions. Section 6 provides a suggested instructional sequence. Section 7 offers suggestions for subsequent research and system evaluation.

Training and Accident Rate Reduction

The importance of training of flight skills has received significant recognition in recent years. On February 12th, 1997, the President of the United States set a national goal of reducing the fatal aircraft accident rate by 80% within 10 years. A broad range of programs has since been set in motion by the Department of Defense, the Federal Aviation Administration, and the National Aeronautics and Space Administration.

The objective of reducing aviation accidents related to human factors shortcomings is addressed in the National Plan for Civil Aviation Human Factors (Hofmann, 1995). Of the five major research thrusts described in that document, two focus on (a) pilot training, and (b) human performance assessment. The NASA Aviation Safety Program Report to Industry (Huettner & Lewis, 1997) specifically cited training as an Aviation Safety Program Investment Area and identified the Aviation Safety Investment Strategy Team (ASIST) for rotorcraft-specific selection and training. A "balanced sample" of 34 accidents was selected by the Helicopter Accident Analysis Team (HAAT) for in-depth analysis and training interventions that might prevent similar accidents were identified. In 9 (26%) of these accidents, simulation facilities were cited and in 11 (32%) of the accidents training for unique operations or maneuvers were cited as potential solutions.

Helicopter Accidents and the Autorotation Problem

According to the National Transportation Safety Board (NTSB) data base, from 1983 through August 1998 there have been 3264 helicopter accidents in the United States, 564 of them fatal. Nearly 300 of the 3264 accidents involved the autorotation maneuver. Iseler (1998) has summarized 1168 of the helicopter accidents in the NTSB data base from 1980 to 1996 and found that various types of *pilot errors, failures, and inadequacies* were cited as "causes" more than any other topic. She also found that the first event in 26% of the accidents was "loss of power inflight," the event that calls for an autorotation maneuver. In a recent analysis of civil helicopter accidents presented by Hart (1998) on behalf of the HAAT, of 1,852 helicopter accidents, autorotation accidents accounted for fully 7% of the total. Such a finding is particularly disconcerting given that the autorotation maneuver is the approved *response* to an emergency, rather than an emergency itself, such as other accident categories of "wirestrike," "loss of tailrotor control," or "fuel starvation." As the HAAT noted, "Although autorotation *per se* is rarely the primary cause of accidents in operational flying, a delayed or improperly performed autorotation can turn an incident into an accident or fatality .... On the other hand, improperly performed autorotations during training flights can damage or destroy aircraft and directly result in serious or fatal injuries."

In a fixed-wing aircraft, when power is lost the pilot establishes a normal glide and begins to search for an airport or other possible landing area. The typical light aircraft glide ratio is approximately 8 to 1; that is 8 feet forward for each foot of altitude lost. At the recommended glide speed and a flight altitude of 5000 feet, the fixed wing aircraft may glide for about six minutes and about eight miles, as the pilot looks for the best landing area. Because the required responses are not unusual, little special training is required for an emergency landing in a fixed-wing aircraft. In a rotary-wing aircraft, however, losing power is a far more demanding situation for the pilot. Although a helicopter does glide with the power off, the glide ratio is usually much less favorable than a fixed-wing aircraft (about 4 to 1 in a Robinson R22), and the time to find a landing area is sharply reduced.

To add to the challenge, the helicopter is typically flying at a much lower altitude than the fixed-wing aircraft when the power loss takes place. In one study (Adams & Taylor, 1986), nearly 75% of helicopter pilots surveyed typically flew below 1500 feet for extended periods of time and performed 4 times as many landings and takeoffs per flight hour as the typical fixed-wing general aviation pilot. At such low altitudes, the helicopter pilot must make an accurate assessment of the situation and issue the appropriate responses, focusing his perceptual, cognitive, and psychomotor capabilities in a very short time frame -- typically seconds rather than minutes.

In a power-off emergency, the pilot's control inputs must be immediate and precise, yet flexible enough to cope with a broad range of unforeseen difficulties, including correcting for any of many possible types of errors made earlier in the autorotation landing sequence. Compared to a fixed-wing aircraft normal glide, performance of the helicopter autorotation maneuver is made much more challenging because of the many types of errors possible. To further clarify the issues, the following subsections describe the nature of autorotation, methods of autorotation training, and the potential for the use of a flight simulator.

What is Autorotation and How is it Performed?

In its simplest description, an autorotation is a maneuver that permits a safe landing without power by trading off the potential energy of altitude plus the kinetic energy of ground speed plus the kinetic energy stored in the rotor system for the thrust needed to land without damage or injury. There is no single "right way" to perform an autorotation, and the specific techniques vary somewhat across helicopter types. In general, however, the principles are the same for every case and are illustrated in Figure 1.

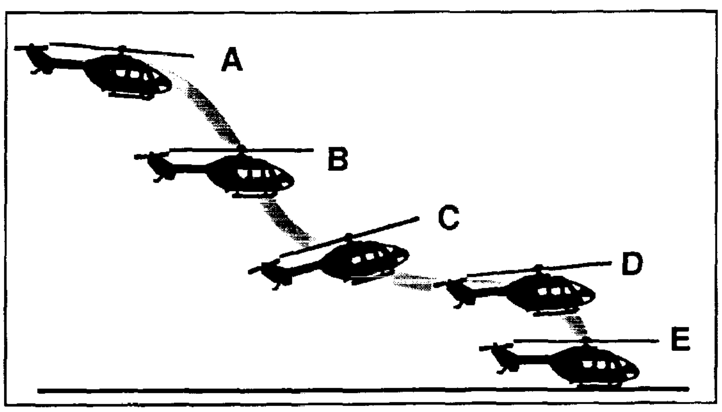

Figure 1. Simplified illustration of the autorotation maneuver.

When the engine fails, the pilot's first steps are (A) to lower the collective completely to maintain rotor RPM, and add right pedal to prevent yawing. Next, the pilot (B) pulls the cyclic aft to reduce airspeed and increase the airflow through the rotor disk, establishes a glide at approximately 65 kts, selects a landing area, and determines how to maneuver for a landing into the wind. If the rotor RPM gets too high during the glide, the pilot must gently lift the collective to increase pitch and lower the RPM. All of the activity described to this point must be performed within a few seconds of engine failure. As the aircraft nears the intended landing area, the pilot initiates a flare (C) (lifting the nose of the aircraft) to reduce the rate of descent and to reduce the ground speed to less than 15 kts. The aircraft is leveled (D) and then landed by lifting the collective at the correct time and speed to produce a soft touchdown (E). The pilot aligns the aircraft with its direction of motion (ground track) to prevent landing gear damage or aircraft rollover.

Although the simple description of autorotation provided above is intended to offer an overview of the maneuver, it also suggests that a catastrophe may occur if the pilot's inputs are incorrect, insufficient, excessive, or poorly timed. The number and nature of the skills the helicopter pilot must master to properly perform an autorotation is intimidating and pilots should receive extensive training in the maneuver.

Limitations of Typical Autorotation Training

Adams (1989) concluded from reviewing the data of available helicopter accident studies at that time that "From the data, it can be concluded that the single factor which offers the largest possible improvement is pilot training." As evidenced by the most recent accident data, performance of autorotation far too often leads to aircraft damage or fatalities. This outcome is not so much due to the danger of the maneuver itself as to the lack of sufficient training in its execution. Because conditions are never exactly the same, experience and judgment are required in order to avoid, or at least recover from, the many possible types of errors (described in Section 2). Extensive training is the only way to acquire the necessary skills for autorotation. Unfortunately, extensive autorotation practice in a helicopter is expensive and risky, and therefore it is rare to devote substantial time to this maneuver. As one instructor puts it, "Autorotations need a lot more attention than they receive in most training establishments" (Coyle, 1998).

In fact, full-touchdown autorotations are very rarely practiced. Both the U.S. Army and Air Force stopped performing them a number of years ago after studies showed that there were more injuries and aircraft damage from practicing autorotation than from autorotations required by actual engine failures. Instead, the autorotation is now taught as two separate activities: (a) the so-called "hovering autorotation" from about 2 to 8 feet above the ground and (b) the "power-recovery autorotation" using a simulated landing area at perhaps 1,000 feet above ground level. The hovering autorotation is not realistic because it begins a few feet off the ground with rolling off the throttle and dropping the collective; unrealistic actions when near the ground in a full-touchdown autorotation. The power-recovery autorotation is not realistic because the visual cues at

1000 feet are different than those nearer the ground, and instead of pulling the collective to cushion the landing on the ground, the engine is brought back up by rolling on the throttle. Also, with the increased torque, left pedal must be applied instead of the right pedal required in a real autorotation.

Very few private helicopter owners permit full-touchdown autorotations for the same reasons as the Army and Air Force -- the costs of damage done by inexperienced pilots are simply prohibitive. Although the financial incentives are clear, many instructors remain convinced that there is no substitute for full touchdowns because "the ballgame is won or lost between the flare and the ground" (Padfield, 1992) and the hovering autorotation and power-recovery autorotation do not adequately provide the student with the flare-to-ground skills needed.

The Potential for Simulator Training of Autorotation

Because in-flight autorotation training is risky, time-consuming, and expensive, it is logical to consider the use of a helicopter flight simulator. Surprisingly, however, prior to our recent work, there were no flight simulators for commercial helicopters (except for head-down instrument training). Their absence may have been simply the result of the economics -- the helicopter flight simulators used by the U.S. Army range in cost from roughly ten million to forty million dollars. At such prices it is highly unlikely that any flight school would be willing to make such an investment.

Now that a cost-effective flight simulator has been developed, it is instructive to consider the utility of its employment for the autorotation task. First of all there is the obvious issue of safety. A simulator reduces the exposure of the student pilots and the aircraft to the hazards of hard landings, rollovers, and other potentially serious accidents, assuming there were opportunities for practice of complete autorotations in the aircraft. But in a very practical sense, a simulator permits practice of the critical tasks (i.e., between the flare and the ground) where real-world practice is not feasible because such training is rarely permitted in the aircraft.

Secondly, there is the issue of cost. This is partially related to the safety issue, because mishaps can be very expensive when they result in aircraft damage. In addition, the cost of flying helicopters is quite high, compared with fixed wing aircraft (approximately $130 per hour in the Robinson R22). A simulator, in contrast, does not require any fuel or maintenance. The only hourly costs after purchase are for electricity and perhaps rental of the floor space to house the simulator. Another cost saving can be realized when sufficient feedback is provided by the computer system during instruction in the simulator so that the constant presence of a flight instructor is not required for practicing the maneuver.

Certainly the virtues of safety and reduced cost are extremely important, but beyond merely serving as substitute for actual flight, simulators can offer at lease 7 specific advantages that are not possible in the aircraft itself. These advantages are described below, although not all of them have been implemented in the current autorotation training simulator.

Demonstrations. The simulator can potentially provide a demonstration of an ideal performance of a maneuver and repeat it as often as the student wishes. Unlike those performed by an instructor, each repetition is identical to the last. The demonstrations can also show how *not* to do the maneuver, presenting common errors and ways to avoid them. Special demonstrations could be offered for variations in aircraft weight, density altitude, wind speed and direction, and so forth, showing how each factor individually, or in combination will effect performance of the maneuver.

Skill development. Skills in which muscular movement is required, but are under sensory control, are known as perceptual motor skills. Such skills include flying a helicopter in which performance of the task is influenced by outside factors to which the pilot must respond to appropriately guide his performance. These skills are more difficult to learn than simple motor skills and potentially benefit from hundreds or even thousands of repetitions (for example, consider learning to play golf or tennis). Unfortunately, for practice in an aircraft, a great deal of time is spent preparing for the maneuver so that only a relatively few autorotations can be done in a session. In contrast, in a simulator a new trial may begin with the press of a button, and dozens of autorotations can be completed in the course of an hour.

Part-task training. As has been described above, there are a number of sub-tasks required in order to perform the autorotation. In the aircraft, it is difficult, if not impossible to practice one part of the task at a time. In the simulator, any part of the maneuver (such as execution of the flare) may be practiced in isolation, perhaps with the instructor critiquing each attempt, over and over again until the student has mastered it. Once the parts are learned, additional practice can be given on smoothly integrating them.

Time manipulation. The simulator provides the capability to manipulate the time element of the task being learned. For example, time can be "slowed," stretching out a critical series of events so that the student can understand their relationships better. Time can also be speeded, either to make the task more difficult, or to condense the lesson, such as in reducing the duration the glide portion of the autorotation. Time can be "frozen" so that the instructor can show the student the nature of the situation that has developed without any further change. Time manipulation can allow error recovery, stepping back to a previous system state. Finally, the entire maneuver, or important segments, can be recorded and replayed so the instructor can critique the students performance when he is not actively involved in flying the aircraft.

Knowledge of results. Knowledge of results of control inputs is critical to learning. In the aircraft, the instructor evaluates the student's performance, but in a general, subjective manner. The flight instructor's main task is to make sure that a catastrophe does not occur. Furthermore, he has no special devices for recording objective flight performance data. In the simulator, every nuance of every event is being generated, and is therefore available for display to the student. Very specific information can be provided as to the appropriateness of control inputs; either instantaneously or immediately after the maneuver. The same kinds of information can be provided to the instructor so that the student's progress may be easily and objectively monitored.

Supplementary cues. Some of the control inputs made by the student do not result in easily observed changes in the course of the maneuver. For example the impact of small changes in glide slope angle on the ability to reach the chosen landing area may not be evident. In the simulator, supplementary cues may be added to aid the student in developing an appreciation of subtle changes in the visual field that will improve his performance (e.g., Lintern, Roscoe, Koonce, & Segal 1990). As Lintern & Roscoe (1980) had previously pointed out, flight is difficult for students because their limited control skills retard effective perceptual learning, and vice versa. Supplementary cues providing good information can simplify the task and permit the student to converge on the correct perceptual cues and control responses.

Adaptive instruction. As the student becomes more proficient at performing the maneuver, the simulator can be programmed to sense this progress and to present a variety of more challenging problems. In this way, a broad range of operational conditions may be presented to generalize the student's skills, and the student continues to be challenged and motivated to improve.

Unfortunately, previously existing helicopter simulators often have been extremely expensive to construct and operate, dependent upon a team of technical support personnel, time-consuming to reprogram, not portable, and in such demand that it is impossible for most researchers to access them, much less flight students. To permit the practical application of an autorotation trainer, construction and operating costs had to be significantly reduced during the initial project work.

Employment of the PRISMS Simulator

A central feature of this autorotation trainer project is the inclusion of an enhanced version of the Pilot-Rotorcraft Intelligent Symbology Management Simulator (PRISMS), shown in Figure 2. PRISMS was developed under an SBIR Phase II contract by Anacapa Sciences and ThoughtWave (Rogers & Asbury, 1999a). It is a powerful, but inexpensive, flight simulator specifically designed to provide many of the features of simulators costing millions of dollars. PRISMS is easy to operate, and is portable for use in a variety of on-site research, demonstration, and training applications.

PRISMS offers an immersive approach with an opaque visor, providing an effective virtual reality experience, as well as an accurate head tracker so that symbology positioning and behavior is appropriately slaved to the user's head movements. The system is configured to simulate flight through terrain generated from digital terrain elevation data as configured in the South Western USA (SWUSA) database. The system includes cyclic, collective, and anti-torque pedal flight controls, a helicopter flight model, voice recognition and synthesis, 3D sound generation, userdefinable symbol appearance and behavior, and extensive, rule-based data recording capabilities. A PRISMS system has been delivered to the Aeroflightdynamics Directorate (AFDD) at NASA-Ames Research Center where evaluation of the autorotation training system will take place.

Figure 2. The PRISMS simulator being flown by an expert pilot.

Section 2. Task Analysis and Typical Error Inventory

Systematic analytical procedures are mandatory for developing flight training devices. This rigorous approach ensures that the training course scope and content ultimately provided is both necessary and sufficient to meet the requirements. We began the project by performing a task analysis to identify the procedural steps in the autorotation, to inventory the information needed to support trainee task performance, and to structure the simulator's practice environment effectively. We then augmented the analysis with an inventory of specific errors in performing the autorotation.

The Autorotation Task Analysis

To simplify the analyses and training issues in this first development of an autorotation simulator, we initially selected the most basic form of autorotation: a straight-in maneuver to a large landing area with no wind or obstacles. In the subsequent improvements to the simulator software, we have added capabilities for introducing wind speed and direction, and training in the ability to land at a particular spot.

The system has also been improved to permit more complex autorotation situations such as 180° turns, 360° turns, S-turns, energy trade-offs for maximum range or minimum range landings, and other advanced techniques. Currently, such maneuvers must be performed with the aid of an instructor. It is anticipated that in subsequent phases of this research, analyses will be performed and software developed to create training materials and metrics specifically applicable to these advanced techniques.

For the purposes of analysis, the overall autorotation sequence was subdivided into the three phases typically described in the helicopter flight training literature: autorotation entry, steady-state descent, and deceleration and touchdown. These three phases were then further broken down into six segments and 17 tasks. Each task was succinctly stated along with the appropriate control element, such as "Control rotor RPM with collective." For each task, the purpose of the task (such as "Avoid rotor over-speed) was stated." Most importantly, the information elements required to perform the task were identified, along with the current source(s) of these requirements. For example, the information requirements for the task cited above are "Rotor RPM and acceptable range," and the information sources are "NR needle and green zone."

In order to validate the task analysis, we conducted a structured interview with subject matter expert Mr. Robin Petgrave, the owner/operator of Bravo Helicopter & Wing at Torrance Airport. Mr. Petgrave estimated that he has performed approximately 24,000 autorotations during the course of flight instruction. During this interview, we reviewed each step in the task analysis to check for missing tasks, incorrectly stated information requirements, or inappropriate information sources. The completed task analysis is shown below.

Phase 1: Autorotation entry

Segment 1: Perform immediate control sequence

Task #	Task	Purpose	Info Requirements	Info Sources
1.	Detect emergency	Prepare for autorotation sequence	Loss of engine power	Auditory cues (silence if engine out in R-22), low rpm horn
				Engine-rotor RPM decay ("needle split")
				Out-of-trim condition (sudden yaw to left)
			Failure in transmission or drive train couplings	Auditory cues depending of failure type
				Rpm increase

Task #	Task	Purpose	Info Requirements	Info Sources
2.	Lower collective completely	Maintain sufficient rotor RPM to prevent loss of aircraft control	Collective position	Arm position
				Control against stops
				Low rpm horn will not sound if collective is all the way down (R-22)
				RPM gauge–if rpm still dropping, collective is not all the way down

Task #	Task	Purpose	Info Requirements	Info Sources
3.	Add right pedal	Prevent yawing, and ensure correct airspeed readings	Aircraft in trim (aligned with direction of travel)	Visual scene
				Trim-strings on R-22
				Kinesthetic cues

Task #	Task	Purpose	Info Requirements	Info Sources
4.	Pull cyclic aft	Prevent pitch-down and increase airflow through the rotor disk to keep rpm up	Pitch attitude	Visual scene
				Kinesthetic cues

Phase 2: Steady-state descent

Segment 2: Establish Normal Glide

Task No.	Task	Purpose	Info Requirements	Info Sources
5.	Set 65-knot airspeed with cyclic	Optimize glide rate	Airspeed	Airspeed indicator

Task No.	Task	Purpose	Info Requirements	Info Sources
6.	Control rotor RPM with collective	Avoid rotor over-speed by gently lifting collective	Rotor RPM vs. acceptable range	(N_R) needle and colored zones
		Avoid rotor under-speed by gently dropping collective	Rotor RPM vs. acceptable range	Audio low-RPM alarm (horn)

Segment 3: Select Landing Area

Task No.	Task	Purpose	Info Requirements	Info Sources
7.	Identify area including poten- tial landing positions	Bound the search area by maximum distance of glide	Maximum glide range (about 4 times altitude)	Altimeter, pilot knowledge
			Glide range at mini-mum rate of descent airspeed (about 3 times altitude)	Altimeter, pilot knowledge, terrain seen below trim string in R-22

Task No.	Task	Purpose	Info Requirements	Info Sources
8.	Reduce area given wind effects		Wind speed	Pilot estimate
			Wind direction	Smoke, dust, estimate

Task No.	Task	Purpose	Info Requirements	Info Sources
9.	Reduce area given terrain problems	Avoid dangerous terrain; seek flat, firm, level ground	Terrain available	Visual scene
			Poles and wires	Visual scene

Segment 4: Maneuver to landing position (straight-in, normal glide)

Task No.	Task	Purpose	Info Requirements	Info Sources
10.	Adjust aircraft heading with cyclic	Heading toward landing position	Landing position	Pilot knowledge
			Aircraft heading	Visual scene

Task No.	Task	Purpose	Info Requirements	Info Sources
11.	Adjust glide path angle with cyclic	Prevent over- or under-shoot	Landing position	Pilot knowledge
			Aircraft glide path	Visual scene

Phase 3: Deceleration and touchdown

Segment 5: Perform the flare

Task No.	Task	Purpose	Info Requirements	Info Sources
12.	Rotate aircraft nose upward w/ cyclic employing appropriate aggressiveness to slow or stop the rate of descent and maintain altitude	Slow or stop the rate of descent, reduce ground speed to <15 kts., and increase rotor RPM (to top of yellow)	Correct altitude to begin flare (about 50 feet in the R-22)	Visual scene (trees, poles to a/c side), "ground rush" (not altimeter)
	Lower collective if necessary to increase rotor rpm.		Rotor rpm at top of yellow	(N_R) needle and colored zones
			Sufficient speed to begin flare (about 50 kts)	Airspeed indicator
			Aircraft gross weight	Pilot knowledge
			Density altitude	Pilot knowledge
			Airspeed at initiation	Airspeed indicator
			Wind speed	Pilot knowledge
			Altitude maintained	Visual scene
			Ground speed < 15 kts	Visual scene

Segment 6: Manage soft touchdown

Task #	Task	Purpose	Info Requirements	Info Sources
13.	Level the aircraft before touchdown with cyclic.	Prevent tail boom strike or porpoising	Aircraft attitude	Visual scene only

Task #	Task	Purpose	Info Requirements	Info Sources
14.	Begin to lift collective at correct moment	Produce soft touchdown	Aircraft begins to sink after flare	Visual scene only

Task #	Task	Purpose	Info Requirements	Info Sources
15.	Lift collective with correct speed	Produce steady pull with maximum collective reached just at touchdown (if maximum collective is necessary)	Collective throw remaining	Left arm position
			Altitude	Visual scene
			Rotor speed decrease	Sound

Task #	Task	Purpose	Info Requirements	Info Sources
16.	Employ aggressive right pedal during collective pull	Maintain heading in direction of motion to prevent rollover	Direction of motion	Visual scene
			Aircraft heading	Visual scene

Task #	Task	Purpose	Info Requirements	Info Sources
17.	Lower collective on touchdown	Reduce slide distance, increase pedal effectiveness	Collective position	Arm position
				Control against stops

The Autorotation Error Inventory

Concurrent with the task analysis, we identified and described the specific types of errors that are most often made in performing the autorotation tasks. These errors were first identified from the literature, and, like the task analysis, were validated in an interview with a subject matter expert. We then reviewed the list of potential types of student errors, identifying the most dangerous and the most common, and the techniques employed to overcome these learning problems.

Although the autorotation is not conceptually difficult, mishaps are possible if the pilot's inputs are incorrect, insufficient, excessive, or poorly timed. It is important to briefly describe these potential errors and their results in order to clarify the number and nature of the skills the helicopter pilot should master. The following list of 13 typical errors is compiled from interviews with subject matter experts and from examples in Coyle (1996), Cantrell (1998) and Padfield (1992).

- Segment 1 Errors: Failure to perform immediate control sequence

  1. *Slowly or incompletely lowering the collective.* Rapid, full lowering of the collective may be the single most important part of an autorotation, ensuring sufficient rotor RPM. If rotor RPM is allowed to decay too much (e.g., below 80% in the Robinson R22) helicopter control will be irretrievably lost and the aircraft will fall like a stone.

  2. *Failing to use the pedals to trim the aircraft.* As the torque produced by the engine stops, the pilot must reduce the anti-torque force by pushing on the right pedal. The autorotation must be conducted with the aircraft aligned with its direction of travel over the ground. Misalignment will also result in erroneous airspeed readings at any point in the autorotation.

  3. *Permitting the nose of the aircraft to drop.* The cyclic should be pulled slightly aft at the initiation of the maneuver. If the nose is permitted to pitch down, it delays the recovery of rotor RPM needed for the maneuver and allows airspeed to build rapidly beyond the optimal glide rate. Subsequently, suddenly pulling the cyclic aft to reduce airspeed may result in a rotor over-speed.

- Segment 2 Errors: Failure to establish normal glide

  4. *Improper control of rotor RPM with collective.* In most helicopters, if the collective is left full down for too long, a rotor over-speed may occur. Another type of mistake is to over-control the collective, lifting and lowering it throughout the glide.

- Segment 3 Errors: Failure to select appropriate landing area

  5. *Failing to select a landing area within the possible zone.* Since there is no way of knowing the exact altitude above the ground, the exact wind speed and direction, or the exact distances to points in the terrain, and since there is no time to consult a graph of rate of descent versus airspeed, the pilot must make a judgement, based on experience, of whether a desired landing position can be reached. Given the unknowns, mistakes will be made.

- Segment 4 Errors: Failure to maneuver to landing position

  6. *Failing to maneuver to the point of intended landing.* Even if the chosen landing position was potentially reachable at the beginning of the maneuver, errors in aircraft control may result in failure to reach the position. This

failure may be due to a variety of errors such as selecting an inappropriate glide speed or misjudging turn timing. The pilot must be able to recognize the errors promptly and know the techniques for countering them, or must select a new landing site.

- Segment 5 Errors: Failure to correctly perform the flare

  7. *Flaring too high.* Although the flare is typically initiated between 40 and 120 feet above the ground, there is no simple rule for choosing the flare altitude. If the flare is too high, there will be insufficient inertia in the rotor to cushion the descent to the ground and a hard landing will result.

  8. *Flaring too low.* The objectives of the flare are to slow the rate of descent and forward speed and to increase the rotor RPM. If the flare is too low, the tail may strike the ground or the pilot must level the aircraft too early resulting in excessive forward ground speed on touchdown.

  9. *Initiating the flare at insufficient speed.* For all helicopters, there is a speed beneath which the flare is not effective in stopping the rate of descent. This speed is usually lower than 40 to 50 kts (53 kts in the R-22). At this speed, bringing the nose up results in the helicopter falling and striking the ground tail first.

  10. *Incorrect flare execution.* The ideal aggressiveness of nose pitch-up depends upon factors such as gross weight, density altitude, wind, and airspeed. More aggressive flares are needed for high gross weight, high density altitude, and less aggressive flares are needed for high wind and high airspeed. Effective flares maintain a constant altitude above ground as the helicopter slows.

  11. *Failure to level the aircraft prior to touchdown.* At the completion of the flare, the aircraft is in a nose-high attitude and must quickly be leveled (by some forward cyclic). Landing in a nose-high attitude will probably result in a tail boom strike or porpoising (landing on the skid heels, rolling onto the toes and flipping forward). A nose-low attitude with high ground speed is almost certain to cause a rollover.

- Segment 6 Errors: Failure to perform soft touchdown

  12. *Pulling up the collective too soon.* If the collective is pulled too early, rotor RPM will decay when the helicopter is too high above the ground, resulting in loss of lift, yaw control, and cyclic control. A hard landing at an inappropriate attitude will follow.

  13. *Pulling up the collective too late.* If the collective is pulled too late, a hard, fast touchdown will occur, possibly with a bounce and loss of control of the aircraft as rotor RPM decreases.

Allowing an incorrect heading at initiation of the slide. If the autorotation is perfect, the slide distance is from zero to a few feet. If ground speed is high, the slide may be much longer. If the heading is not identical to the helicopter's direction of travel, the landing gear may catch and roll the aircraft onto its side. Typically, aggressive right pedal is needed during the collective pull because the tail rotor loses effectiveness as RPM decreases.

Section 3. Training, Learning, and Instructional Analyses

Based on the task analysis, a series of additional analyses was performed to identify specific instructional goals, the information needed to support learning, and the best employment of the unique advantages of the flight simulator.

Hierarchical Training Analysis

We employed the completed task analysis as a structure for identifying instructional goals. Our first step was to identify the instructional goals in terms of "terminal behaviors" (approximately corresponding to the task analysis segments) that identify what the learner will be able to do at the end of the training session, such as "perform immediate autorotation control sequence." Next, the terminal behaviors were broken down into hierarchies of subordinate skills (approximating the analysis tasks) required such as "lower collective completely", and "pull cyclic aft to maintain rotor rpm."

In addition, we specified the applicable conditions for performance, such as "within 2 seconds," or "at 65 ± 5 knots." These conditions both amplify the nature of the supporting knowledge and skills as well as to lead directly the creation of test items based on the performance objectives. These analytical procedures, while systematic, depend upon expertise of the analysts, and upon interaction with the user community to ensure that no items are overlooked and that the applicable conditions are accurate. We have interviewed an expert instructor to supplement the analysis from available written training materials. Nevertheless, because many of these performance metrics have never before been so precisely measured, some additional evaluation of their acceptable ranges may be necessary.

- Terminal Behavior 1: Perform immediate autorotation control sequence
  - Skill 1: Detect Emergency
    - Initiate collective down movement in less than 1.5 sec after engine out.
  - Skill 2: Lower collective completely
    - Push collective full down in less than 2.0 sec. after engine out.
  - Skill 3: Maintain aircraft in trim (± 5°)
    - Add right pedal (primarily taking out left pedal to even)
    - Initiate movement within 1.5 seconds after engine out.
  - Skill 4: Pull cyclic aft to maintain rotor rpm
    - Initiate movement within 1.5 seconds after engine out.
- Terminal Behavior 2: Establish normal glide
  - Skill 5: Set 65 ± 5-knot airspeed with cyclic
    - 65 ± 5-knot airspeed achieved within 10 seconds after engine out.
    - 65 ± 5-knot airspeed maintained until flare initiation
  - Skill 6: Control rotor RPM with collective
    - Continuously maintain rotor RPM in acceptable range (97% to 104%) ("In the green")

Skill 3a: Maintain aircraft in trim
Hold heading error of less than ± 5° throughout the glide

- Terminal Behavior 3: Perform the flare

    Skill 7: Rotate aircraft nose upward with cyclic
    - Initiate flare at 40 to 50 feet
    - Initiate flare at greater than 53 knots airspeed
    - Slow rate of descent to 0-5 feet/sec maximum
    - Reduce ground speed to less than 15 knots
    - Increase RPM to no more than top of yellow zone (110%)
    - Reduce RPM to no less than 97%

    End flare at acceptable altitude (less than 10 feet)

- Terminal Behavior 4: Manage soft touchdown

    Skill 8: Level the aircraft before touchdown
    - Hold aircraft pitch attitude within ±5° at start of collective pull

    Skill 9: Begin to lift collective at correct moment
    - Begin collective pull as aircraft begins to sink after flare

    Skill 10 Lift collective with correct speed
    - Pull collective steadily with maximum reached just at touchdown

    Skill 11: Employ aggressive right pedal during collective pull
    - Hold aircraft in trim (± 5°) at touchdown

    Skill 12: Lower collective on touchdown
    - Push collective full down within 0.5 sec. after touchdown

Learning Analysis and Instructional Analysis

A learning analysis goes beyond the task analysis in that it identifies information needed to support learning, and not just that to perform the task. Given the definition of skills required and information available in the cockpit, we attempted to match specific training strategies and techniques to the nature of the instructional goals. For example, various briefings, demonstrations, coaching, or monitoring may be needed to make practice sessions more effective. Certain tasks require extensive practice, and others benefit from special visual cue augmentation.

We also performed an instructional analysis, which is similar to the learning analysis but stresses the employment of the simulator's unique advantages. In this case we attempted to match the difficult perceptual-motor components of specific autorotation skills to potential Instructional Support Features (ISFs) of the simulator system. ISFs may be defined as simulator hardware and software capabilities that allow the instructor or an automated system to manipulate, supplement, and otherwise control the learning experience of the student to maximize the rate and level of skill acquisition. As an example of an ISF, the instructor might choose to temporarily "freeze" a maneuver so that the student has more time to observe the visual scene and the aircraft's momentary attitude.

For the purposes of this initial effort, we have assumed that the students will be qualified in the R22 and familiar with the basic concepts of autorotation. It is expected that they will have performed hovering autorotations and power-recovery autorotations, but will never have performed a complete autorotation all the way to the ground. Thus, any necessary briefings will be specific to the autorotation maneuver and to the PRISMS features provided for instruction and performance measurement.

As we performed the learning and instructional analyses, we were disappointed to find a surprising paucity of published research directed at these issues in the flight simulation domain. That is not to say that there are not hundreds of training guidelines (e.g., see Sweezy & Llaneras, 1997). However, it appears that research on matching of training techniques and ISFs to specific flight tasks, or even to general classes of psycho-motor skills has been grossly neglected. It seems that technological sophistication has taken priority over demonstrated training utility of the instructional features. For example, although we have identified fifteen types of ISFs based on modern simulator technology, we found not a single guideline stating the task characteristics and conditions for which one of these ISFs would be best used. As a result, our approach was to use basic learning principles and subject matter expert judgements in matching these techniques and ISFs to the terminal behaviors and related skills required in the autorotation.

Key Training Strategies for Autorotation Training

Skills in which muscular movement is required, but are under sensory control (such as most sports activities), are known as perceptual-motor skills. Such skills include flying a helicopter in which performance of the task is influenced by outside factors to which the pilot must respond in order to appropriately guide his performance. Two of the traditional strategies for instructing perceptual-motor skills are providing knowledge of results, and providing extensive practice. More recently, the strategies of providing augmented cues and part-task training have been shown to be valuable. These four training strategies are described below.

Knowledge of results. Knowledge of results is defined as the feedback that is provided to students to indicate how well they performed on a task. This instructional strategy has been extensively studied and it is abundantly clear that knowledge of results of is critical to learning, and that the rate of learning depends upon the precision of the results provided to the students.

Although it would seem that flying a real aircraft would provide the optimal knowledge of results, this is not always so. For example, the multiple effects of flight control inputs can cloud the meaning of the feedback. Furthermore, neither the flight instructor nor the aircraft has any special devices for recording and directly indicating the precise qualities of the student's actions.

In contrast, in the simulator, every bit of information used to generate the flight simulation is potentially available for display to the student and the instructor. Precise information can be provided regarding the appropriateness of every control input; either immediately or at the end of the maneuver or session. In addition this information can be saved for review in later sessions so that the student's progress may be easily and objectively monitored. In the results screens that students will see in the PRISMS autorotation trainer, 30 specific metrics will be presented so that the student can see exactly how well he has performed and whether the performances on each metric fall within their accepted ranges.

Supplementary practice for skill development. Perceptual-motor skills are difficult to learn and may continue to improve after hundreds or even thousands of repetitions. For example, consider the number of trials necessary to learn to accurately hit baseballs, golf balls, and tennis balls. For each of these activities, machines and practice areas have been developed to permit the student to greatly supplement the number of balls strikes that might be made in an actual game so that much more practice can be achieved per unit time.

In the case of practicing autorotations in an aircraft, a great deal of time is spent climbing to altitude and preparing for the maneuver so that only a relatively few autorotations can be done in a session; perhaps 8-10 on the course of an hour. However, in the PRISMS autorotation trainer a new trial may begin with the press of a button, and it is probable that 50 –60 self-paced autorotations could be completed in the course of an hour, complete with precise knowledge of results. Once the basics of the system and the maneuver are understood by the student, an instructor's presence is unnecessary and the student may continue to practice the maneuver for as long as the system is available.

Augmented cues. A substantial amount of practice is necessary to acquire proficiency in landing an aircraft largely because of the need to develop the required perceptual judgment abilities. Unfortunately, the limited flight control ability of the student pilot actually restricts perceptual learning. As described by Lintern & Roscoe (1980, p.232):

> During contact flight instruction in an airplane a trainee relies on imprecise cues for information about the actual and desired flight paths and attitudes to guide control behavior. This effectively retards development of control skills because the appropriate control inputs cannot be made consistently until the student pilot can interpret the strange new visual scene sufficiently well to know when the airplane is in the correct position and attitude. In a circular fashion, limited control skill will retard the desired perceptual learning because the student cannot experience the correct perceptual cues if the airplane does not follow the correct flight path.

One strategy for avoiding this unfortunate situation is to somehow change the training display, augmenting the available cues, so that the student is led to correct perceptions and control inputs from the very beginning of training. From that point, the student can begin to develop an appreciation of subtle changes in the visual field that will improve his performance.

Augmented cues providing useful information can simplify the task and permit the student to much more rapidly converge on the correct perceptual cues and control responses. The difficulty, however, is that this improvement must be done in such a way that the student does not become overly dependent upon the augmented cues, so that successful task performance requires their presence.

Furthermore, the augmentation should be used to highlight the important information in the scene that will be present in the real-world application. Thus, it is important to use pictorial rather than symbolic cues so that the student focuses on spatial relationships among real-world objects as opposed to simply following some instructions from a flight director-like display.

For example, Lintern, Roscoe, & Sivier (1990) showed transfer of training with augmented pictorial displays to be vastly superior to that from symbolic displays of landing performance. The augmentations they employed, shown in Figure 3, included a set of eight pairs of "F-poles" facing each other. The horizontal distance between the vertical poles and the vertical distance between the horizontal arms represented the correct approach path to the runway touchdown point. In addition, a flight path predictor, shown as a small aircraft symbol near the center of the figure, indicated the azimuth and elevation directions of the predicted aircraft velocity vector, as well as the roll of the aircraft.

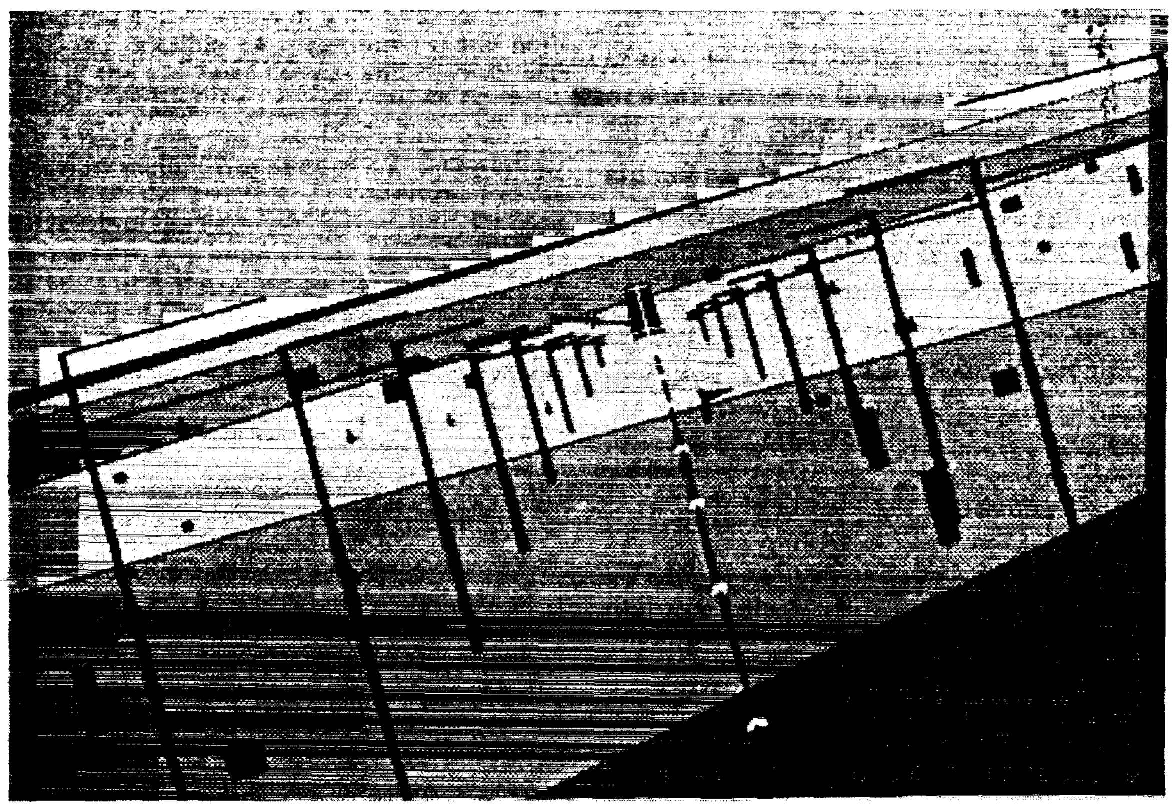

Figure 3. The F-poles and flight path predictor used by Lintern et al. (1990).

The symbolic display, shown in Figure 4, provided corresponding information, including a command guidance circle, a flight path predictor airplane symbol, aircraft attitude, flight path angular errors, heading relative to the runway and range to the runway aimpoint. In effect, all of the necessary spatial information was available, but it was not presented by spatial displays, pictorially linked to the students view of the earth.

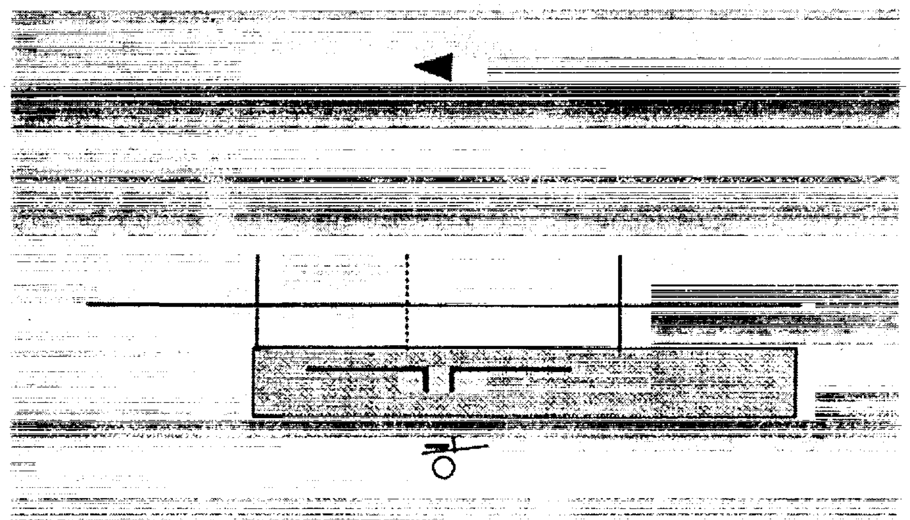

Figure 4. The symbolic display used by Lintern et al. (1990).

The experimental results showed that the effects of display type were quite strong and persistent. For lateral control, training with the symbolic displays produced virtually no transfer of training, but the pictorial displays yielded high and enduring transfer. In the case of vertical control, the transfer effects again were clearly superior with the use of pictorial displays. This transfer advantage strongly suggests that it is important for students to learn something about the spatial relationships among elements in the natural visual scene. In contrast, if only patterns of control inputs stored as motor memory were necessary, the symbolic display should have resulted in at least equal transfer of training, which did not occur.

Because there is some well-founded concern that a student could develop a dependence on augmented cueing systems (e.g., Lintern and Roscoe, 1980), Lintern et al. (1990) attempted to avert this danger by removing the augmented cues from view whenever the student's simulated aircraft was within acceptable error limits, thus forcing primary dependence on intrinsic perceptual information presented by the non-augmented scene. However, when the authors compared performance from a group using this adaptive approach with another group receiving continuous augmentation cues, they found that the anticipated dependency on the cues did not take place. The authors hypothesized that continuous augmentation may not produce a dependency effect "if it effectively directs attention to salient elements of a control strategy."

Although the research on augmented cues has been primarily on visual cues, augmented auditory cues might also be useful in certain circumstances. Auditory cues might take the form of synthesized voice cueing and coaching, or of more representational sounds such as engine and rotor sounds enhanced to provide more distinct cues to aircraft conditions.

Part-task training. As the autorotation task analysis showed, there are a number of skills required in order to perform the autorotation. In the aircraft it is difficult, if not impossible, to practice one part of the task at a time (although the hovering autorotation and the power-recovery autorotation are attempts to divide the maneuver into two segments). In the simulator, however, any part of the maneuver may be repeatedly practiced in isolation, with the instructor or an automatic system critiquing each attempt, until the student has mastered the required skills. Once the parts are learned, additional practice can be given on smoothly integrating them.

Part-task training has not always been found to be advantageous. Some experimental studies (e.g., Goettl, 1994; 1995) have found no advantage or even some disadvantage of part-task training. However, the effectiveness of part-task training must depend on just how the whole task is decomposed into parts. There are three types of part-task training: segmentation, fractionation, and simplification. Segmentation is a method for partitioning on temporal or spatial dimensions, such as performing the final segment of a task first. The subtasks may then be practiced alone, or in groups, and then recombined into the whole task. Fractionation is used to separate two or more subtasks which are normally executed simultaneously (such as controlling pitch and roll in an aircraft). A part-task trainer could permit automatic control of one variable while the other was actively practiced. Simplification is a method in which a task is made easier by adjusting some task characteristic, such as control-display lag.

An excellent review of the literature on these three types of part-task training is found in Wightman & Lintern (1985). In summarizing the research, these authors found that the segmentation procedure using "backward chaining" to be the most effective of the part-task techniques. The fractionation and simplification methods were usually less effective than whole-task training, although both have produced positive transfer of training and could be useful if part-task training was relatively inexpensive.

As an example of the use of the segmentation procedure, Wightman & Sistrunk (1987) taught college students carrier-landing final approach skills in a simulator. The students were assigned to a control group or one of three different training strategies and were then tested on the criterion configuration (identical to the control training method). The segmentation group performed segments of the carrier landing task beginning at 2,000 feet from touchdown, then 4,000 feet, then 6,000 feet. Subjects trained under this backward chaining segment procedure performed better on transfer to the whole task than did those trained only in the whole task. The authors conclude that these subjects learned more quickly because they made fewer errors in the early trials.

Because they began at the correct glideslope, angle of attack, and lineup, and were close to the carrier deck, they had fewer opportunities to accumulate large errors before touchdown, and thus practice was more useful to them than for those who began 6000 feet from the carrier.

The autorotation maneuver, however, is not directly analogous to the carrier landing. First of all, because obtaining the proper autorotative glideslope (to a large landing area) is relatively easy, large errors are unlikely to accumulate prior to the flare and touchdown activities. Secondly, the critical control inputs for the autorotation flare, aircraft leveling, and soft touchdown performed in the last few seconds are not direct extensions of the final approach, as they are in the carrier landing task. As a result of these differences, the backward chaining segment procedure is unlikely to aid in autorotation learning.

Nevertheless, a part-task training technique may be useful in producing a 'building-block" approach to autorotation training, ensuring that the basic tasks are mastered first and that the most difficult tasks may be isolated for intensive practice. It would certainly make sense, for example, to ensure that the each of the four critical segments of the autorotation is mastered before the next one is attempted, both because the earlier segments are easier and because errors in earlier segments could be catastrophic thus ending the session before later segments could be practiced.

Instructional Support Features (ISFs)

As stated earlier, ISFs include simulator hardware and software capabilities that allow the instructor/operator to manipulate, supplement, and otherwise control the learning experience of the student to maximize the rate and level of skill acquisition. In order to efficiently review the history of instructional support features (ISFs) typically offered by flight simulation systems, we searched the Anacapa Sciences archives for descriptions of ISFs available in various Army flight simulators. We found 15 types of features that have been use over the past 20 years that are potentially applicable to an autorotation simulator. A brief description of each type is provided below.

- **Automated Maneuver Demonstration** allows the instructor to select prerecorded demonstrations of flight maneuvers. The recordings may be viewed from inside or outside the aircraft. Special supplementary symbols may be required to indicate the positions of the flight controls used to achieve the aircraft position and orientation. Prerecorded narratives describing each maneuver may also be valuable in the automated demonstration.
- **Automated Adaptive Training** automatically varies parameters of a task as a function of the performance level of the student. As the student becomes more proficient at performing the maneuver, the simulator can sense this progress and to present a variety of more challenging problems. In this way, a broad range of operational conditions may be presented to generalize the student's skills, and the student continues to be challenged and motivated to improve.

- **Malfunction Insertion** allows the instructor to insert and delete a number of system malfunctions. Once the malfunction is inserted, its effect on both aircraft controllability and on other aircraft systems will occur unless the student performs the appropriate emergency procedures.
- **Instructor Console Display** provides the instructor with access to a variety of flight condition and simulation condition information. Information is displayed in pictorial, graphic, and alphanumeric formats. Informational content of the console displays varies with the training application.
- **Problem Freeze** allows all simulator parameters (e.g., flight control, propulsion, motion, visual cues, etc.) to be fixed at the values that exist when the freeze is initiated. The entire simulation is frozen so that the instructor can show the student the nature of the situation that has developed without any further change. The freeze can then be released by the instructor and the flight continues.
- **Parameter Freeze** enables the instructor to hold constant the value of individual flight parameters. Examples of parameters that can be frozen include: altitude, airspeed, heading, bank, pitch, yaw, vertical speed, torque, rotor RPM, rate of turn, and fuel load. The parameter freeze is particularly useful for beginning students learning to understand the control functions.
- **Initial Conditions Set** allows the instructor to select one of several preprogrammed training conditions. For each of these preprogrammed training conditions, values of a collection of aircraft condition environmental condition, and geographic location parameters, are selected. Slight modifications to values of certain parameters, such as ceiling height, wind direction and velocity, etc., may be permitted at the beginning or during the conduct of a training exercise.
- **Initial Condition Modification** permits the instructor to create a completely new set of initial conditions. Set modification is accomplished by selecting a preprogrammed initial conditions set and changing each parameter value as desired prior to conduct of the training session. The resultant new set can be saved under another name and selected as desired
- **Automated Performance Alerts** signal the instructor that some aspect of performance has exceeded previously specified tolerances. For example, color-coded performance parameters may appear on the instructor's screen to indicate out-of-tolerance conditions with specific numeric indications of the error level.
- **Automated Cueing** provides for automatic presentation of messages to the student when an out-of-tolerance condition exists. Cueing messages identify the specific out-of-tolerance element (e.g., "check altitude," "check airspeed") without describing the problem. The virtue of cueing is that it forces the student to practice seeking out the information. Voice synthesis may be employed for the messages.
- **Automated Coaching** automatically presents coaching messages to the student when an out-of-tolerance condition exists. Coaching messages identify the appropriate action to eliminate the out-of-tolerance condition (e.g., "return to 1000 feet, " increase airspeed to 100 knots"). Voice synthesis may be employed for the messages.

- **Automated Checkride** allows the instructor to present a number of standard checkrides. Selection of this feature configures the simulation at preselected aircraft parameters and begins a prerecorded set of instructions. The student is required to perform each of the checkride tasks in the order in which they are identified.
- **Automated Performance Measurement** provides automatic monitoring, recording, processing, and display of quantitative performance measures. Generally, tolerance bands established around numerous performance values are used to identify out-of-tolerance conditions. The ISF records the duration and time of occurrence for immediate display at the instructor console and for later hard copy printout, as desired.
- **Record and Replay** allows the instructor to record and replay previous performances. Visual and motion cues, control inputs, instrument readings, and inter-cockpit communications may also be replayed. In modern simulators such as PRISMS, the viewpoint of the replay can potentially be moved to various positions inside or outside the aircraft to better observe the maneuver
- **Error Printout System** provides hard copy printouts of pilot performance metrics during the training session. The system prints a log of the metrics including instances of out-of-tolerance flight conditions and the times when they occurred. In newer simulators, the errors may be temporarily viewed on the instructor's or student's display as an alternative to producing hard copy.

ISF Matrix

In summary, we were able to identify 4 training strategies and 15 ISFs that are potentially applicable to autorotation instruction with the PRISMS simulator. To further examine the applicability of these training strategies and features to the autorotation situation, we constructed a matrix for evaluating the utility of each of them to the four terminal behaviors and 12 subordinate skills necessary for performing the autorotation. In addition to the 4 strategies, we added columns for two specific examples of augmented visual aids: guidance poles and flight path markers. The utility of these two visual aids in aircraft landing instruction has been previously demonstrated (Lintern et al., 1990) and should certainly be attempted using the PRISMS simulator. We also added a column for augmented auditory aids.

We initially planned to place dots in the cells of the matrix for which prior research had shown the utility of the strategy or ISF in instructing the terminal behavior or skill. Having completed the learning analysis and the instructional analysis, however, we found very few research studies that were helpful in identifying such relationships for the ISFs. We found no specific guidelines indicating the task characteristics and conditions under which the ISFs would be best used. It is likely that simulator manufacturers do not view their role as including experimental research on training and that instructors provided with the simulators are tasked with training, and not the conduct of controlled experiments. Thus, in completing the matrix, our approach was to use a combination of basic learning principles, common sense, and our own expertise in attempting to match the ISFs to the terminal behaviors and related skills required in the autorotation.

The row titles of the matrix are the terminal behaviors and component skills required for the conduct of the autorotation maneuver. The column titles are the four training strategies (and the three additions) and the fifteen ISFs, in the order of their presentation above. The dots shown in the cells of the matrix indicate the potential applicability of a strategy or a feature to the terminal behaviors and skills. Typically, the applicability is to an entire terminal behavior such as "Perform the flare," but in some cases refers to specific individual skills. For example, knowledge of results and supplemental practice are applicable to all of the terminal behaviors and all of their subordinate skills. Augmented auditory aids, in contrast, are applicable primarily to unambiguously presenting the changing sounds apparent at engine failure (in Skill 1) and the low-RPM horn (in Skills 2 and 6).

The matrix proved useful in defining simulator requirements, described later in this report. By serving as a reminder of potential opportunities for enhancing PRISMS characteristics, the matrix aided in directing the blending of creative and technological efforts required for development of the autorotation trainer's capabilities. The uses of the ISF matrix will be discussed in more detail in the following section of the report.

Table 1. Simulator Instructional Support Features and Training Strategies Potentially Applicable to Terminal Behaviors and Skills.

Terminal Behaviors and Skills	Knowledge of Results	Supplemental Practice	Augmented Visual Aids (AVAs)	AVA- Guidance Poles	AVA- Flight Path Markers	Augmented Auditory Aids	Part-Task Training	Maneuver Demonstrations	Adaptive Training	Malfunction Insertion	Instructor Console Display	Problem Freeze	Parameter Freeze	Initial Condition Sets	Initial Conditions Modification	Performance Alerts – Instructor	Automated Error Cueing	Automated Error Coaching	Automated Checkride	Performance Measurement	Record and Replay	Error Print-Out
TB 1: Perform immediate control sequence	•	•					•			•	•			•	•	•	•	•	•	•		•
Skill 1. Detect Emergency	•	•				•														•		•
Skill 2. Lower Collective Completely	•	•	•			•											•	•		•		•
Skill 3. Add Right Pedal	•	•	•										•				•	•		•		•
Skill 4. Pull Cyclic Aft	•	•															•	•		•		•
TB 2: Establish Normal Glide	•	•			•		•	•	•		•	•		•	•	•	•	•	•	•	•	•
Skill 5. Set 65-Knot Airspeed with Cyclic	•	•															•	•		•		•
Skill 6. Control Rotor RPM with Collective	•	•				•											•	•		•		•
TB 3: Perform the Flare	•	•	•	•	•		•	•	•		•	•	•	•	•	•	•	•	•	•	•	•
Skill 7. Rotate Aircraft Nose Upward	•	•																		•		•
Skill 8. Level Aircraft Before Touchdown	•	•																		•		•
TB 4: Manage Soft Touchdown	•	•	•				•	•			•	•		•	•	•			•	•	•	•
Skill 9. Begin Collective Pull at Correct Time	•	•																		•		•
Skill 10. Lift Collective at Correct Speed	•	•	•																	•		•
Skill 11. Employ Aggressive Right Pedal	•	•											•							•		•
Skill 12. Lower Collective on Touchdown	•	•																		•		•

Section 4. Definition of Simulator Requirements

There are three major topics in defining simulator requirements. These include (a) the identification of simulator fidelity requirements, (b) the definition of simulator characteristics to support training strategies and techniques, and (c) the specification of performance measurement capabilities. Each of these topics is discussed in the following pages.

Simulator Fidelity Requirements

We established the PRISMS autorotation simulator fidelity requirements through examining the outcomes of the task analysis and other analyses described in the preceding sections and a review of the technical literature. There are several critical issues to be addressed in assessing the required simulator fidelity. These include the simulator flight model, the cockpit displays and controls, the cockpit motion cues, and the outside visual scene.

The simulator flight model. The standard flight model employed in PRISMS was designed to approximate the handling qualities of the AH-64 Apache aircraft. Because most helicopter students will have received training in the Robinson R22, significant changes in PRISMS flight handling qualities were required. In addition, the original model was configured for use only in powered flight. The aerodynamics of autorotation impose a number of additional requirements upon the aircraft response to control inputs. During powered flight, engine power is used to overcome rotor drag. When the engine fails, rotor drag must be overcome by adjusting the collective pitch and aircraft attitude so that airflow through the rotor provides sufficient energy to maintain rotor rpm. The rotor disk is divided into three regions: the *driven* region, the *driving* region, and the *stall* region, each with different lift and drag characteristics during autorotation. Pilot control inputs that alter airspeed, rotor rpm, blade pitch, and rate of descent, change the relationships among the three regions in ways too complex to be described in detail this report. In any case, it was evident that substantial changes and enhancements to the flight model would be required for a realistic autorotation simulator.

Cockpit displays and controls. As the task analysis made clear and the experts confirmed, the only instrumentation required for performing the autorotation is airspeed and rotor rpm. Although it would have been easy to present this information as screen-fixed symbology in the HMD, we felt some additional training value might be provided by locating it on the instrument panel as it is in the Robinson R22 (as aircraft-fixed symbology). Because the HMD does not provide sufficient resolution to present precise copies of the airspeed indicator and rotor tachometer, we elected to abstract out the critical ranges and markings of the two displays and employ moving horizontal bars as needle metaphors, as shown in Figure 5. In this solution, the slightly off-axis location of the displays is realistically maintained and, additionally, the console may be used in conjunction with the horizon as a pitch cue during the flare.

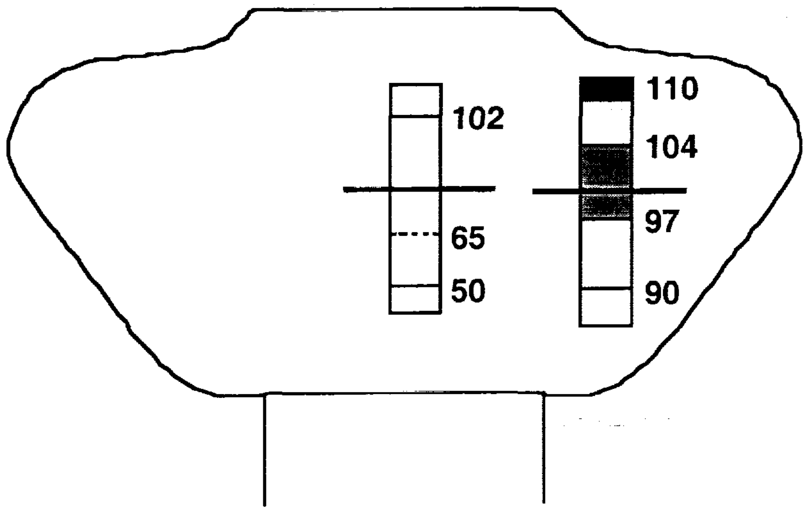

Figure 5. The abstracted simulator airspeed and rotor rpm indicators.

Although not strictly required for performing the autorotation, the trim strings attached outside the canopy on the R22 were also provided in the simulator. These simple strings show the airflow across the canopy, and thus the trim of the aircraft. The trim strings are expected to prove useful in improving the accuracy of aircraft trim judgments given the resolution limitations in depicting the terrain.

It was evident at the outset that realistic collective, cyclic, and pedal controls would be required for the simulation. The collective and pedal controls furnished with the PRISMS system were judged to be appropriate without further modification. The PRISMS cyclic control, however, is a center-loaded, side-mounted stick. One alternative was to purchase a new center-mounted stick (such as the Flight Link G-Stick II). The other alternative was simply to remove the grip-centering springs from the current cyclic and maintain the side-mounted position. We elected to use the latter approach since the Flight Link cyclic is not similar to the R22 "T-bar" cyclic and because the cyclic location is probably of much less importance in training than is the accuracy of the specific control inputs made by the pilot.

Cockpit motion cues. Although the resources available for this project would not have permitted the acquisition of a motion base, it is instructive to consider the potential utility of such equipment in the future. Our exploration of the literature led us to conclude that simulator motion cues, while capable of providing somewhat realistic vestibular and kinesthetic sensations, are not particularly useful in improving flight control performance. Jacobs & Roscoe (1980), for example, argue quite persuasively that motion-base systems are largely sold on the basis of spurious arguments and that, in fact, "complex cockpit motion, whether slightly beneficial or detrimental on balance, is not worth much; it has so little effect on training transfer that its contribution is difficult to measure at all."

Any argument for a motion base simulator for autorotation is further weakened given that the autorotation maneuver should be smoothly executed with little or no g forces experienced by the pilot, so that such cues would be unlikely contribute to mastering the maneuver. Furthermore, the addition of simulator motion carries certain risks. If the cues thus provided are incomplete, delayed, or otherwise different from those normally experienced in the aircraft itself, then the training value of the simulator may actually be reduced, and simulator sickness may be more likely, especially for those familiar with the actual aircraft (Stark, 1989). Given these findings, it is unlikely that a motion base is necessary or useful for an autorotation simulator.

The outside visual scene. The most important source of information for the pilot performing the autorotation is the outside visual scene. As shown in the task analysis, except for glimpses at the airspeed and rotor rpm indicators, the pilot is primarily dependent upon the cues he receives from the outside scene to detect aircraft trim, prevent pitch-down during autorotation entry, identify the landing area, maneuver to the landing position, perform the flare, and manage the soft touchdown.

There are about 30 factors that influence simulator image quality, including a variety of physical image properties such as field size, resolution, luminance, and contrast. In discussing the outside visual scene, however, we will restrict our attention to the factors that are directly involved in aiding aircraft handling at low altitudes through provision of cues to depth and self-motion.

Although the binocular depth cue of retinal disparity is available with a two-channel HMD system, monocular cues usually provide more useful depth information, especially at distances beyond 10 or 20 meters. Monocular depth cues include relative angular object size, texture gradient density, object interposition, linear perspective, height in the visual field, atmospheric haze, visible detail, relative luminance and motion parallax.

The detection and estimation of self-motion, of course, is dependent upon the changes in the appearances of objects and textures in the visual scene. Thus, increasing the number of objects visible in the scene increases the accuracy of the perception of self-motion. For example, Kleiss and Hubbard (1993) showed that the speed and accuracy of detecting altitude change in a flight simulator improved with increases in the density of vertical objects in the scene (1, 3, 13, or 51 objects). An example of the scenery used in this research is shown in Figure 6.

In these experiments, complex terrain texture improved detection of altitude change, but did not alleviate the need for high object density, while adding detail to individual objects to increase their natural appearance (such as depicting pine trees versus simple tetrahedrons) produced no performance improvements. In addition, with more objects present in the scene, the motion parallax cue becomes a considerably more important source of distance relationships. Motion parallax refers to the appearance of nearer objects moving faster over the retina than more distant objects when the viewer's head is moved. With continuous self-motion, this cue becomes extremely useful in determining the speed and direction of that motion. Determining the direction of self-motion is also aided by "optic flow," the expanding pattern of approaching objects around the direction of self-motion.

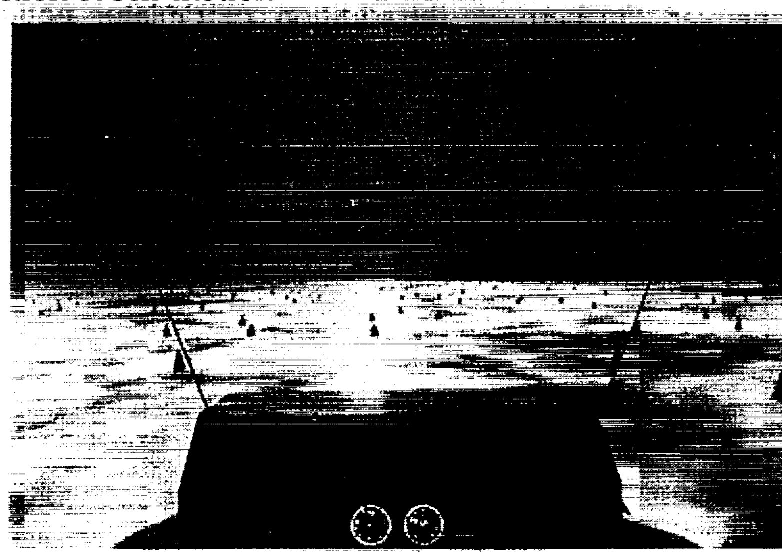

Figure 6. Scene with a high density of pine trees on textured terrain (Kleiss and Hubbard, 1993).

In order to provide satisfactory cues to depth and self-motion in the PRISMS autorotation trainer we employed a variety of depth and motion cues, consistent with the appearance of actual airfields. We have replaced the landing field in the original trainer with a new and much more detailed Army model. The new landing area is depicted in Figure 7. This figure shows a portion of the model of an actual private airfield in West Palm Beach, Florida. The view is one looking down Runway 9, where a number of hangars, a tower, and various other structures can be seen within the field of view.

These objects provide excellent cues of relative angular object size, object interposition, linear perspective, and height in the visual field for use in determining aircraft altitude and rate of change of altitude. The runway surface depiction includes a realistic wear and stain pattern useful in providing more easily discriminated distance cues at low altitudes than were previously available. The changing angular size of the runway and its markings provide additional cues to aircraft altitude.

Characteristics to Support Training Strategies and Techniques

We examined the results of the learning and instructional analyses, as summarized in Table 1, and attempted to identify the most useful training strategies and

ANACAPA SCIENCES, INC.

October 6, 2000

Code JIT
Ames Research Center
Mail Stop 241-13
Moffett Field, CA 94035

Dear Code JIT:

Enclosed is one copy of our final report for NASA Order Number A61839D(ANG) supplementing the autorotation trainer work on our previous Contract NAS2-99075.. Another four copies have been sent to the COTR, Loran Haworth at Mail Stop 210-5. The report is entitled *A Flight Training Simulator for Instructing the Helicopter Autorotation Maneuver (Enhanced Version).* It includes all of the material from the initial phase of work, and is substantially augmented with descriptions of our recent improvements to the system.

In particular, it provides descriptions of the three new capabilities: 1. Incorporation of visual training aids to assist the student in learning the proper appearance of the visual scene when the maneuver is being properly performed; 2. Introduction of a requirement to land at a particular spot, as opposed to the wide, flat open field previously used, and provision for appropriate metrics of success; and 3. Inclusion of wind speed and wind direction settings (with selectable random variability) to add a more realistic challenge in "hitting the spot."

If there is any further information regarding the report or the conduct of this project, please do not hesitate to call me at the telephone number or email address below.

Sincerely,

Steven P. Rogers
Principal Scientist
(805) 966-6157 ext. 14
sprogers@anacapasciences.com

SPR/bag
Encl.

301 E. Carrillo Street, P.O. Box 519, Santa Barbara, California 93102-0519, 805-966-6157
Other Anacapa Offices: Charlottesville, Virginia; Fort Rucker, Alabama

Table A2–1. NASA STI Database Subject Divisions and Categories

AERONAUTICS
01 Aeronautics (General)
02 Aerodynamics
03 Air Transportation and Safety
04 Aircraft Communications and Navigation
05 Aircraft Design, Testing, and Performance
06 Aircraft Instrumentation
07 Aircraft Propulsion and Power
08 Aircraft Stability and Control
09 Research and Support Facilities (Air)

ASTRONAUTICS
12 Astronautics (General)
13 Astrodynamics
14 Ground Support Systems and Facilities (Space)
15 Launch Vehicles and Space Vehicles
16 Space Transportation
17 Spacecraft Communications, Command and Tracking
18 Spacecraft Design, Testing, and Performance
19 Spacecraft Instrumentation
20 Spacecraft Propulsion and Power

CHEMISTRY AND MATERIALS
23 Chemistry and Materials (General)
24 Composite Materials
25 Inorganic and Physical Chemistry
26 Metallic Materials
27 Nonmetallic Materials
28 Propellants and Fuels
29 Materials Processing

ENGINEERING
31 Engineering (General)
32 Communications
33 Electronics and Electrical Engineering
34 Fluid Mechanics and Heat Transfer
35 Instrumentation and Photography
36 Lasers and Masers
37 Mechanical Engineering
38 Quality Assurance and Reliability
39 Structural Mechanics

GEOSCIENCES
42 Geosciences (General)
43 Earth Resources
44 Energy Production and Conversion
45 Environment Pollution
46 Geophysics
47 Meteorology and Climatology
48 Oceanography

LIFE SCIENCES
51 Life Sciences (General)
52 AeroSpace Medicine
53 Behavioral Sciences
54 Man/System Technology
55 Planetary Biology

MATHEMATICAL AND COMPUTER SCIENCES
59 Mathematical and Computer Sciences (General)
61 Computer Programming and Software
62 Computer Systems
63 Cybernetics
64 Numerical Analysis
65 Statistics and Probability
66 Systems Analysis
67 Theoretical Mathematics

PHYSICS
70 Physics (General)
71 Acoustics
72 Atomic and Molecular Physics
73 Nuclear and High-Energy Physics
74 Optics
75 Plasma Physics
76 Solid-State Physics
77 Thermodynamics and Statistical Physics

SOCIAL SCIENCES
80 Social Sciences (General)
81 Administration and Management
82 Documentation and Information Science
83 Economics and Cost Analysis
84 Law and Political Science
85 Urban Technology and Transportation

SPACE SCIENCES
88 Space Sciences (General)
89 Astronomy
90 Astrophysics
91 Lunar and Planetary Exploration
92 Solar Physics
93 Space Radiation

GENERAL
99 General

instructional support features for each of the four terminal behaviors and 12 component skills.

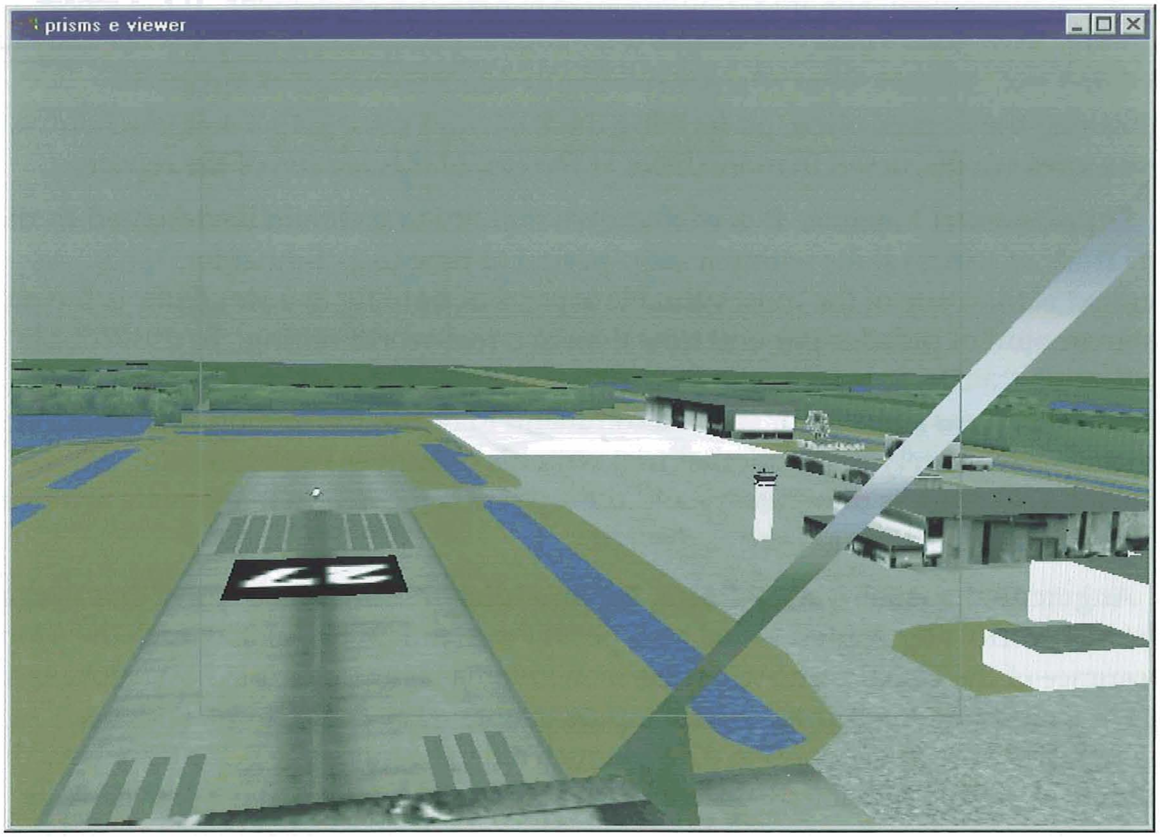

Figure 7. The landing field currently used in the autorotation trainer.

Knowledge of Results. Feedback to the students regarding how well they are performing the task is extremely important and will be provided in great detail, using 33 performance metrics. Various feedback elements are provided to the students at appropriate points in the training sessions. For example, during the time that the student is mastering the immediate control sequence required after engine failure, the session concludes with a results screen visible on the student's HMD and the instructor's console such as the one shown in Figure 8.

COLLECTIVE MOVEMENT	1.035	SEC
COLLECTIVE FULL DOWN	1.654	SEC
RIGHT PEDAL MOVEMENT	1. 123	SEC
CYCLIC AFT MOVEMENT	1. 562	SEC

Figure 8. Results feedback for immediate control sequence performance.

In this screen, the four metrics are the response times for beginning to move the collective downward, moving the collective to the full-down position, beginning the right pedal movement, and initiating the aft cyclic control movement. If the scores are within the acceptable range, the results will be shown in green; if they are not, they will be colored red. Similar types of screens will provide knowledge of results for establishing the normal glide, performing the flare, and managing a soft touchdown. These scores are discussed in more detail at the end of this section of the report.

Supplemental Practice. It is well-known that training should be designed to allow many trials of critical skills within a short period of time (e.g., Schneider, 1985). As described earlier, one of the most valuable aspects of training in a simulator is the much greater amount of practice per unit time than in a real-world setting. In the PRISMS autorotation trainer, as soon as the student has reviewed the performance feedback screen he can press a button or speak a command to return the session to it's starting point and immediately begin another trial with his objectives fresh in mind. An instructor's presence is unnecessary and the student can perform maneuvers at a rate of about one per minute for as long as desired.

Augmented Visual Aids: F-Poles. By providing information beyond that available in the real world, augmented visual cues permit the student to quickly learn the proper appearance of the visual scene when the maneuver is being performed correctly, and assist in instructing the correct control inputs to obtain the desired visual scene. Although there are many ways to provide such aids, the guidance poles developed by Lintern et al. (1990), previously described and shown in Figure 3, have proved to be valuable in instructing fixed-wing landings. Thus, we have elected to use a similar cue system in the PRISMS autorotation trainer. This cue, shown in Figure 9, was recently completed and appears to the authors to be quite effective. The student is instructed to fly through the spaces defined by the arms of the pairs of the F-poles, keeping the subsequent pair aligned with the current pair, and to avoid venturing above or below the glideslope thus indicated.

At the instructor's option, eight pairs of poles will appear at the time of simulated engine failure. The poles are evenly distributed in distance over the 2000 feet to the touchdown point, and become successively shorter as they approach the airfield. Although the student's primary job is to correctly monitor and control heading, airspeed and rotor rpm, the relationships of the F-poles pictorially indicate how well the student is doing and how the spatial relationships of the real-world scene should appear during the autorotation glide and flare. The difference between the glideslopes for the powered fixed-wing aircraft simulated by Lintern et al. (1990) and an unpowered rotary-wing aircraft (approximately 4° versus 14°) do not seem to impact the utility of this visual training aid. The final pair of F-poles are not aligned with the normal glideslope, and are used to provide cues for flare initiation. The height of all poles was established by trial and error to fit the "school solution" of the autorotation profile. It is understood that there is a family of profiles that would produce a successful landing.

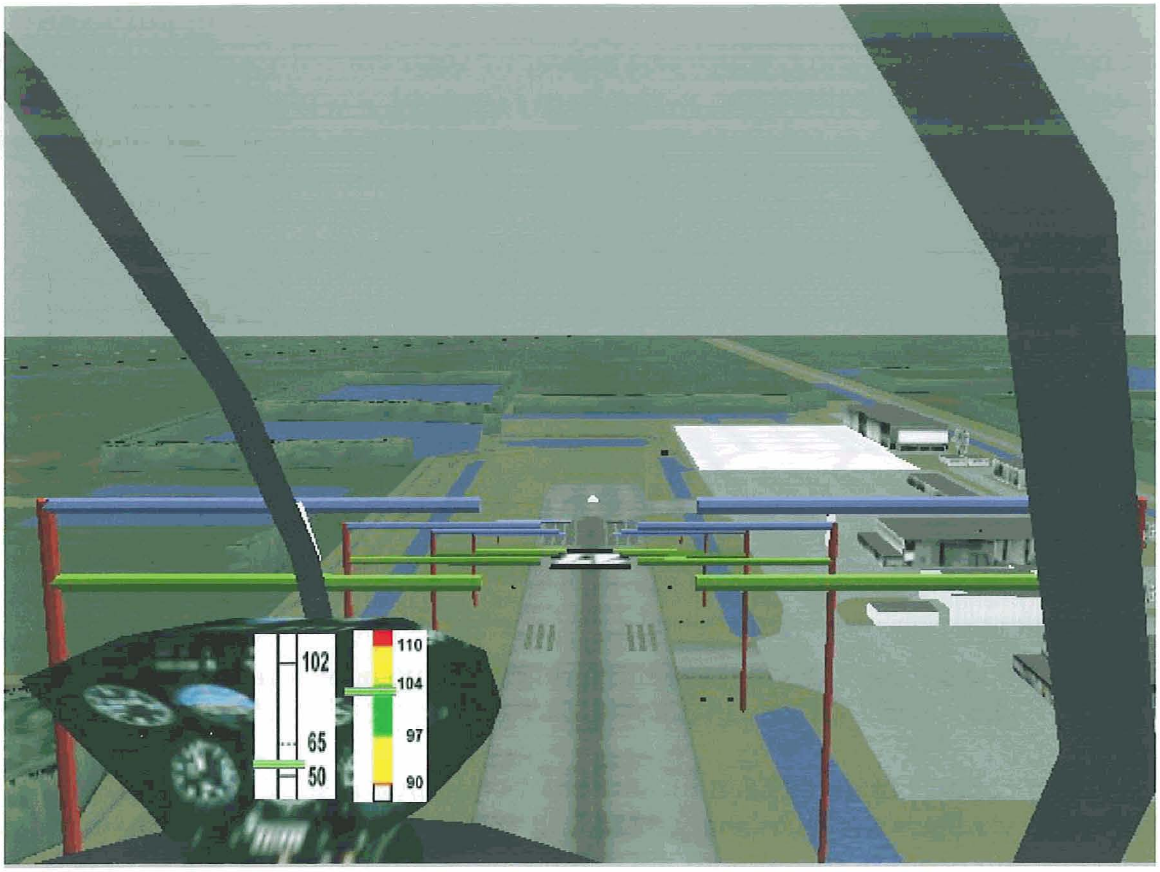

Figure 9. The F-poles augmented visual aid for glideslope visualization.

Augmented Visual Aids: Flight Path Marker. In recent years, we have experimented with a new HMD symbol called the flight path marker (FPM), which also provides some very useful spatial cues for precision landings. The development of the FPM symbol, which may be used with or without the F-poles, is described below.

Although an aircraft "velocity vector" is currently shown (screen-fixed) in the AH-64 Apache IHADSS symbology, it is depicted as a line extending from the center of the HMD screen toward the direction of aircraft movement (as seen from above). The length of the line indicates the aircraft velocity. This symbol is very useful for hovering, but provides no cues to the relationship between the moving aircraft and surrounding terrain features. Instead, what is needed for an autorotation training cue is a 90° transformation of the vector so that the pilot can look along the axis of the vector to determine the continuously computed direction of flight or point of terrain impact if no further control inputs are provided.

The FPM we designed is a simple, unfilled circle with two "wings" to distinguish it from other round symbol elements. It shows the continuously computed velocity vector of the aircraft. The pilot can use it to see exactly where the aircraft will fly or, contact the ground, if control inputs do not change. A somewhat similar symbol, usually called a "climb-dive marker," has been applied in fixed-wing military aircraft, but has always been presented with reference to the aircraft's axis. The FPM is more useful because it is not tied to aircraft heading, which in a helicopter sometimes does not correspond to the vector of motion. Furthermore, as shown in Figure 10, it is implemented so that the symbol "grows" in size as the impact point becomes nearer to the aircraft, and it begins flashing on and off at 3 seconds to ground impact to alert the pilot.

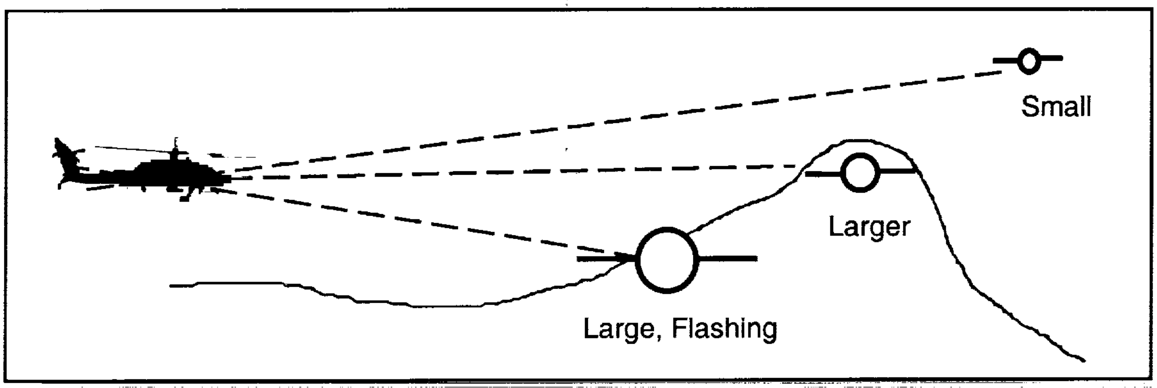

Figure 10. Appearance of the flight path marker symbol and example of the symbol changing size as the potential impact point nears the aircraft.

The appearance of the FPM in the autorotation trainer is shown in Figure 11, below. Also visible is the igloo-shaped landing spot indicator, which clearly marks the desired landing position throughout the maneuver. Before the flare, the FPM is seen on the ground well short of the landing point. In this figure, the pilot has initiated the flare and the FPM indicates that the current aircraft vector is slightly high and to the left of the target landing spot.

The authors, although very much impressed with the FPM's utility in flight with helmet-mounted displays, are uncertain regarding it's potential as an autorotation training device. While the F-poles provide pictorial cues useful in establishing the correct spatial relationships, the FPM provides the kind of symbolic data that was shown in the Lintern et al. (1990) studies to produce little or no transfer of training. Because it provides such clear and accurate information, it would be very tempting for the student to simply use the FPM as a primary indicant of performance rather than learning the more subtle cues necessary for successful autorotation in the real world.

In any case, the F-poles and the flight path marker are intended to be used early in training and discontinued as the student learns the appearance of spatial relationships in the visual scene when the maneuver is being performed correctly. No data is currently available that would indicate how many trials should be conducted with these aids. Thus, the instructor's judgement will be called upon for the initiation and cessation of these visual aids. It is possible, however, to adaptively control their presence, based on the quality of the student's performance. For example, they might be presented only when the flight performance errors exceeded certain limits.

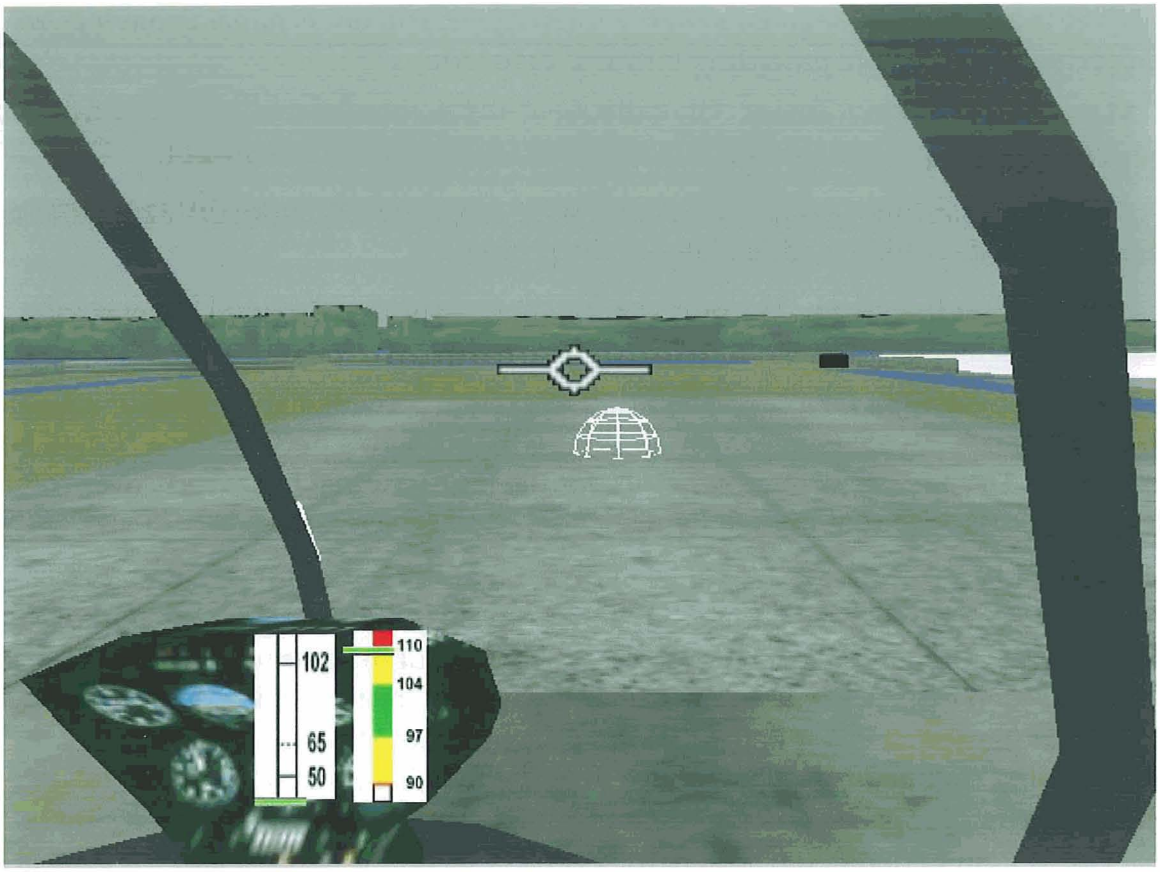

Figure 11. Appearance of the flight path marker symbol and the landing spot indicator in the autorotation trainer field of view during the flare.

Augmented Auditory Aids. PRISMS will employ its voice synthesis capability to provide automated cueing messages to the student. For example, the synthesized voice will speak the words "check trim" and "check airspeed" as an indication for the student to scan his displays. In addition, the realistic and useful cues of engine sounds, engine failure, low-rpm horn, and other such auditory cues will be included in the trainer.

Part-Task Training. A segmentation of the four terminal behaviors will be employed to ensure that the basic tasks are mastered before the most difficult ones. In the autorotation, the tasks increase in difficulty, beginning with the simple reactions to engine failure, to the more complex control inputs for entering the normal glide, and the most difficult tasks of the flare and touchdown. Thus, the student will perform Terminal Behavior 1, the immediate control sequence, until it is mastered before progressing to practice Terminal Behavior 2, establish normal glide. Mastery is tentatively defined as performing the control sequence within the acceptable time constraints three times in a row. That is, after the screen shown in Figure 6 appeared with all characters presented in the green color three times in a row, the next trial will include both Terminal Behaviors 1 and 2. When Terminal Behavior 2 is mastered, Terminal Behavior 3 will be added, and so on. Because the entire autorotation maneuver is brief and its segments highly interdependent, no terminal behaviors will be performed without the preceding terminal behavior.

Maneuver Demonstrations. Digitally recorded demonstrations of the autorotation as performed by expert pilots could be added in later stages of the project.

Adaptive Training. Adaptive training with progressively more difficult wind and terrain conditions could be added later in the project.

Malfunction Insertion. The only malfunction currently provided is the engine failure itself. Other failures could be added in subsequent years.

Instructor Console Display. The PRISMS system provided an instructor console with a variety of viewable screens for observing the student's performance. It will be supplemented by the performance metrics for the four terminal behaviors, with color codes for success or failure of each item.

Problem Freeze. The problem freeze stops all of the simulator parameters so that the instructor can discuss the situation that has developed during performance of the autorotation. Although the problem freeze is very useful in fast-moving situations, it has often proved disconcerting to the student when the freeze is released and the flight suddenly continues. It is our belief that the difficulties are directly related to the student having changed control positions during the freeze so that these control positions are inappropriate when motion resumes. Thus, we have devised a simple visual cue system to depict the both correct control positions and the current control positions. The student must move the controls to their correct positions before the flight can continue.

Parameter Freeze. This ISF is primarily useful for beginning flight students and is not included in the PRISMS trainer. If necessary, the instructor can employ his joystick control to aid the flight so that the student is not required to operate all of the controls at once, just as is typically done in the real aircraft during initial training.

Initial Condition Sets. Any number of initial condition sets can be provided. The default set for the PRISMS autorotation trainer includes the standard landing area and engine failure altitude. Provisions have been added to permit the instructor to construct initial condition sets including engine out position, landing spot position, airspeed, heading, altitude, and winds. These features are described in Section 5 of the report.

Initial Conditions Modification. The instructor may modify the initial conditions set to suit his requirements. The changes may be momentary, or may be permanently saved as a new set.

Performance Alerts – Instructor. The Instructor will receive the same performance alerts as shown in Figure 8, although it is possible for the PRISMS system to provide many others if they are judged to be useful.

Automated Error Cueing. Synthesized voice cues will be provided during Terminal Behavior 2, when establishing the normal glide, to warn the student of trim and airspeed errors. During the other autorotation segments, the course of events is generally too rapid to benefit from error cueing.

Automated Error Coaching. The error cueing solution will be used instead of error coaching because it forces the student to determine the nature of the problem and determine what action should be taken.

Automated Checkride. Essentially, the autorotation trainer may be considered a checkride as well as an instruction device. No additional special provisions will be made for this ISF.

Record and Replay. Digital recording for replay and viewing either inside the aircraft, or outside the aircraft from any desired viewing position may be provided during later phases of the project

Error Print-Out. All of the metrics gathered by the PRISMS autorotation trainer are saved on the system hard drives and may be printed out as desired for use in student evaluation, conduct of experiments, or long-term storage.

Performance Measurement Capabilities.

PRISMS is designed to permit gathering of nearly any performance metrics, using rule-based logic so that sophisticated measurements may be made. We have selected 33 measurements of autorotation performance based upon the task analysis and the review of common autorotation error types. These specific performance measurements are described in more detail below, and in Section 5 of this report.

1. Perform Immediate Control Sequence
    - Collective movement. Time in msec. to initiate collective movement after engine failure.
    - Collective full down. Time in msec. to bring the collective to its full down position after engine failure
    - Right pedal movement. Time in msec. to move the right pedal forward after engine failure.
    - Cyclic aft movement. Time in msec to move the cyclic aft after engine failure

2. Establish Normal Glide
    - Time to glide airspeed. Time in seconds to establish normal glide airspeed (65 ± 5 knots).
    - Out of airspeed range. Number of events during the glide in which airspeed is not within the 60 – 70 knot airspeed range.

- Out of airspeed range. Cumulative time in seconds during the glide in which airspeed is not within the 60 – 70 knot airspeed range.
- Out of rpm range. Number of events during the glide in which the rpm is not within the 97-104 rpm range.
- Out of rpm range. Cumulative time in seconds during the glide in which the rpm is not within the 97-104 rpm range.
- Out of trim range. Number of events during the glide in which the yaw trim error exceeds ± 5°.
- Out of trim range. Cumulative time in seconds during the glide in which the yaw trim error exceeds ± 5°.
- Glide ratio achieved. The ratio of horizontal travel to altitude loss during the glide.

3. Perform the Flare
   - Flare altitude. Altitude in feet above ground level at which the cyclic is pulled aft to initiate the flare.
   - Flare airspeed. Airspeed in knots at which the cyclic is pulled aft to initiate the flare.
   - Minimum descent rate. Minimum rate of descent in feet per second experienced during the flare.
   - Minimum airspeed. Minimum airspeed in knots experienced during the flare.
   - Low rotor rpm. Minimum rotor rpm experienced during the flare.
   - High rotor rpm. Maximum rotor rpm experienced during the flare.
   - Maximum pitch. Maximum aircraft pitch-up angle in degrees experienced during the flare.
   - End of flare altitude. Altitude above ground level in feet at which the cyclic is pushed forward to level the aircraft.

4. Manage Soft Touchdown.
   - Collective pull altitude. Altitude in feet above ground level at which collective pull began.
   - Collective at touchdown. Amount of collective pull in percentage of the full range achieved at touchdown.
   - Trim at touchdown. Trim error in the yaw axis in degrees off-center experienced at touchdown.
   - Roll at touchdown. Roll error in degrees off-center experienced at touchdown.

- Pitch at touchdown. Pitch error in degrees off center experienced at touchdown.
- Collective full-down. Time in msec. at which collective returned to its full-down position after ground contact.
- Tail rotor strike. If applicable, the detection of a tail rotor strike during the flare or touchdown.

5. Overall Measures of Autorotation Success
   - Sink rate. Rate of descent in feet per second at the moment of ground contact.
   - Rotor speed. Rotor rpm in percent at the moment of ground contact.
   - Forward velocity. Velocity of aircraft horizontal movement in knots at the moment of ground contact.
   - Longitudinal error. Meters beyond or short of the target spot at the moment of ground contact.
   - Lateral error. Meters left or right of the target spot at the moment of ground contact.

Section 5. Implementation of Autorotation Training in PRISMS

This section of the report describes the specific implementation of the training system requirements discussed in Section 4. Section topics include the simulator flight model; aircraft, cockpit, displays, and controls; the operational environment; experimental control and monitoring; and student control of training sessions.

The Simulator Flight Model

Blade Element Rotor Model. A finite blade element model was constructed to generate appropriate main rotor rpm and thrust for the autorotation flight model. The lift and drag coefficients for the NACA 0012 airfoil are used as an approximation to the Robinson R-22 main rotor. This flight model is implemented using a new PRISMS object named 'helicopter dynamic' that is run in a new PRISMS process named subject2.

De-coupling the helicopter dynamics from the rendering loop provides a significant increase in both frame rate and dynamics fidelity. The rendering process (subject) no longer has to await the dynamics calculation to take a simulation time-step. In addition, the dynamics calculation does not have to await the rendering process to produce the next simulation view. Both operations are fully overlapped and information shared across the PRISMS attribute network.

Main rotor dynamics are computed from the standard lift and drag equations. Aerodynamic forces on the main rotor are derived to generate the overall thrust and drag values. Pilot controls manipulate the collective pitch used to generate the angle of attack for each blade. As inflow dynamics change based on the orientation of the helicopter to the direction of flight, independent thrust and drag components are computed from the relative angle of attack for each blade element.

As usual, the thrust component is used to move the helicopter. The drag component, however, is used to derive the main rotor rpm for the next time step and generate a torque about the thrust axis of the helicopter. As the helicopter descends and increases the vertical inflow through the rotor system, the drag components for some of the blade elements become negative and tend to increase the angular velocity of the rotor system. When the sum of all blade elements produce a negative value, the rpm of the main rotor is increased as a function of the mass of the main rotor blades.

Conversely, when the drag value is positive, the main rotor rpm is decreased unless the engine is producing enough power to overcome it. In the case where the engine is producing sufficient power to overcome rotor drag, the rotor drag is transmitted to the helicopter as a torque about the thrust axis. A simple model for the tail rotor is used to generate a pilot controlled torque about the thrust axis in order to control heading and overcome engine torque. The tail rotor model uses the disc diameter, disc loading and pedal input to generate the anti-torque forces.

Helicopter Dynamics Parameters

Figure 12 presents the attributes of the helicopter dynamic object. The attribute values shown below were selected to approximate the behavior of the Robinson R-22. To simulate other helicopter rotor systems, each of these attributes may be changed to reflect the characteristics of desired rotor system.

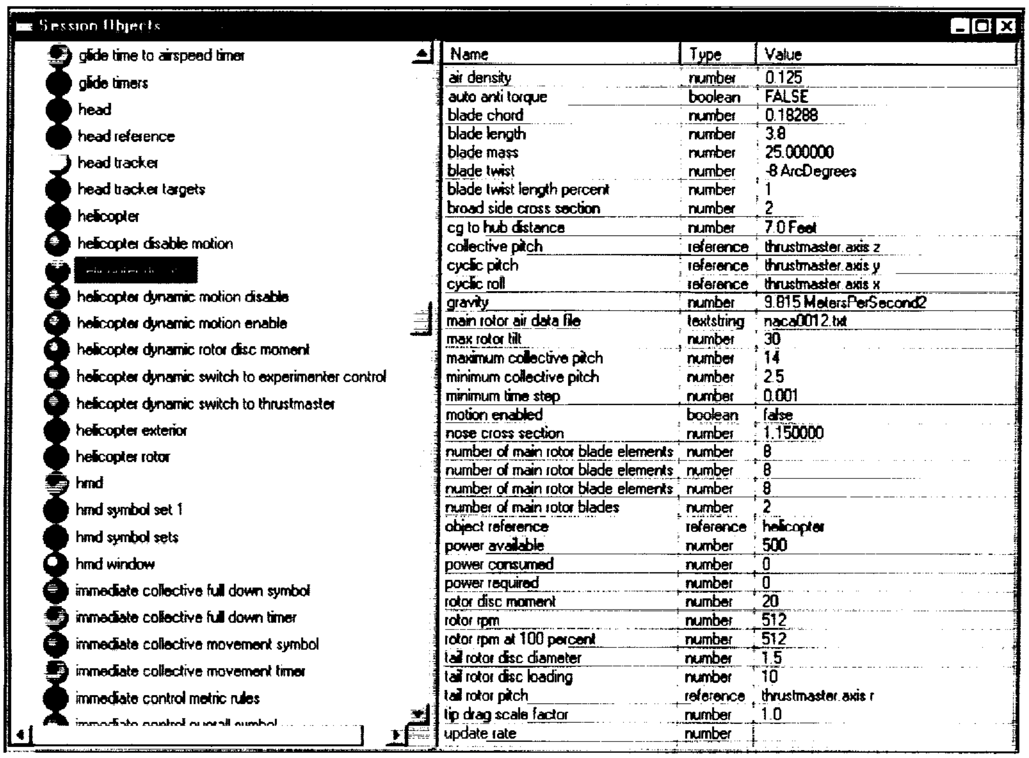

Figure 12. Helicopter dynamics object attributes.

Flight handling qualities are dramatically affected by manipulating the attributes shown above. For example, to reduce the sensitivity of the cyclic, reduce the max rotor tilt from 30 to 15. This will give the pilot improved attitude control over a smaller range. The units for dimensional quantities are meters or square meters. Angles are specified in degrees and time in seconds. "Air density" is specified in kilograms (mass) per cubic meter.

The new "rotor disc moment" attribute is used to control the dynamic behavior of rotor and is specified in kilograms (mass) * meters2. Increasing this number will create a more massive rotor system that is more resistant to changes in rotational velocities. Decreasing this number creates a less massive rotor system that responds much more quickly to aerodynamic forces.

The PRISMS Autorotation Training Session directly manipulates several of these values. For example, the "kill engine" and "engine on" derivations specify values for the "power available" attribute. When configuring a different blade model, it is important to check the "power required" attribute to see how much will be needed to overcome drag. Additionally, the mass of the helicopter object should be checked for errors, such as using a Blackhawk main rotor on a vehicle with the weight of a Robinson.

Aircraft, Cockpit, Displays, and Controls

Robinson R-22 exterior model. The Robinson R-22 is represented in PRISMS by three distinct 3D models: the exterior, interior, and main rotor. Figure 13 presents a view of the exterior model of the R-22. This model is used to present a realistic view of the flight to the experimenter's chase view. In order to improve the frame rate for the subject, this exterior model is not seen by the pilot.

Rotor RPM, Trim, and Airspeed Indicators. The interior of the R-22 was constructed separately from the exterior. This reduces the overall number of polygons that the subject viewer has to consider rendering. Figure 14 presents a view from the cockpit when the helicopter is at its initial position.

In order to make the instruments more readable in a reduced resolution helmet mounted display, enhanced airspeed and rpm indicators were constructed, as described in Section 4. These indicators are magnified replicas located in close proximity to the actual instrument. The green "needle" provides the instrument indication.

Just above the airspeed indicator, there is a barely visible "white trim string" connected to the center separator of the forward canopy. This "trim string" indicates the direction of the relative wind with respect to the orientation of the helicopter. When the string is pointing to the right, then relative wind is from the left.

Control Position Indicators. Unlike real aircraft, simulated aircraft can be artificially stopped and started from arbitrary positions and orientations. During these "freeze" and "fly" operations, the pilot is suddenly placed in a situation without precise knowledge of appropriate control positions for this flight regime. This lack of information regarding appropriate control positions can initially cause extreme unwanted deviations from the intended flight profile when a flight is initiated in the air with significant velocity.

To provide the pilot with information on the appropriate control positions, the set of symbology shown in the lower center portion of Figure 14 was created. The box depicts the maximum control deflections for the cyclic, collective, and pedal controls. The cross hair in the center indicates the current position of the cyclic and the large white circle in the box indicates the desired position for the cyclic. The triangle and circle along the bottom of the red box are for the pedal positions and the symbols on the left side of the box are for collective positions.

Figure 13. Robinson R-22 exterior model.

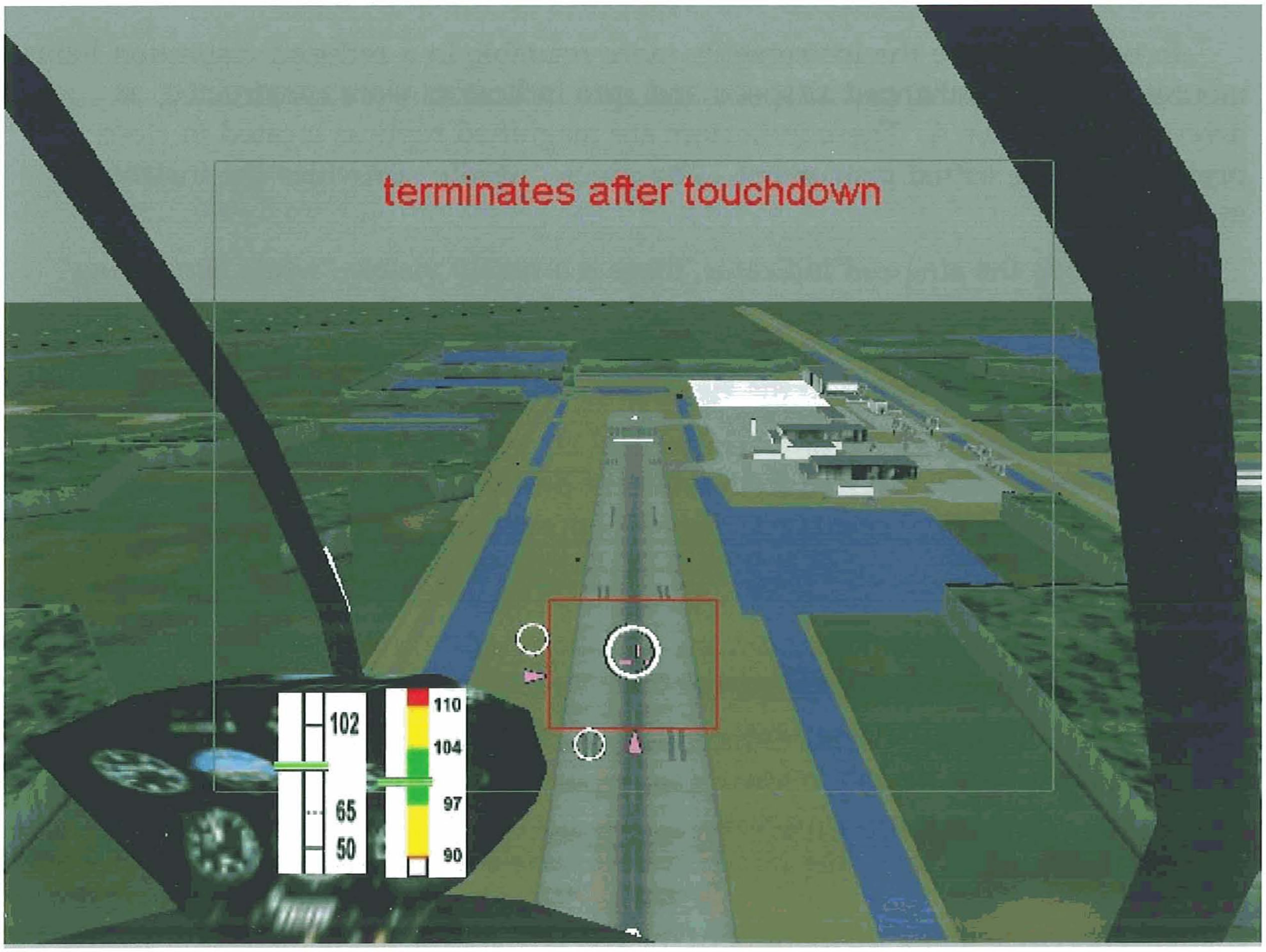

Figure 14. R-22 cockpit view from the initial position.

All the pilot needs to do in preparation for flight is manipulate the controls so that the position indicators are located in their respective circles. When the simulation is "frozen", the current control positions are remembered to allow the pilot to resume flight without dramatic perturbations in the flight path. At the beginning of the Autorotation maneuver, the initial control positions are set by the "initial condition control targets for reset" derivation. This derivation employs the following three attributes of the "experimenter control values" object to set the target control positions: "initial control position collective", "initial control position cyclic", and "initial control position pedal".

Operational Environment

The Airfield Model. An airfield model, shown in Figure 14, is provided with a single runway 9/27. The straight-in autorotation maneuver is performed on runway 9 and terminates near the numbers for 27. Terminating the maneuver at this location provides the greatest number of peripheral cues from buildings just south of the runway.

The F-Pole Enhancement of the Landing Area. In order to provide the pilot with a glide path reference during the autorotation maneuver, the F-Poles shown in Figure 9 were constructed. The poles are 500 feet tall, 100 feet wide and 2 feet in diameter. Each pair of poles is placed along the runway such that there is a gap of 50 feet between the tips of the poles. The gap can be modified by changing the "F Pole control values", "offset" attribute from its' default of 125 feet. All eight pairs of F-poles are evenly spaced between the initial and ending locations for the autorotation maneuver.

The Initial and Ending Position Markers. Two wire-frame spheres are used to mark the engine out and intended landing positions. The engine out position marker, named "waypoint engine out", is only useful to the experimenter, since it is directly below the subject and can't be seen through the helicopter. The intended landing position marker, named "waypoint", provides the pilot with a visual reference to the spot from which landing metrics are obtained. Either or both of these markers can be easily removed by setting the "disable visual" attribute to true.

The Flight Path Marker. To further support the pilot's ability to accurately control the helicopter's flight path, the flight path marker (FPM) image symbol was constructed. This symbol indicates the direction of the helicopter's velocity vector on the pilots display. It is updated dynamically and provides direct feedback regarding the effect of control input manipulation on the flight path of the helicopter.

Experimental Control and Monitoring

Control and Status. The primary control and status screen for the experimenter is shown in Figure 15. This screen is one of six that provide information on the subject pilot's flight.

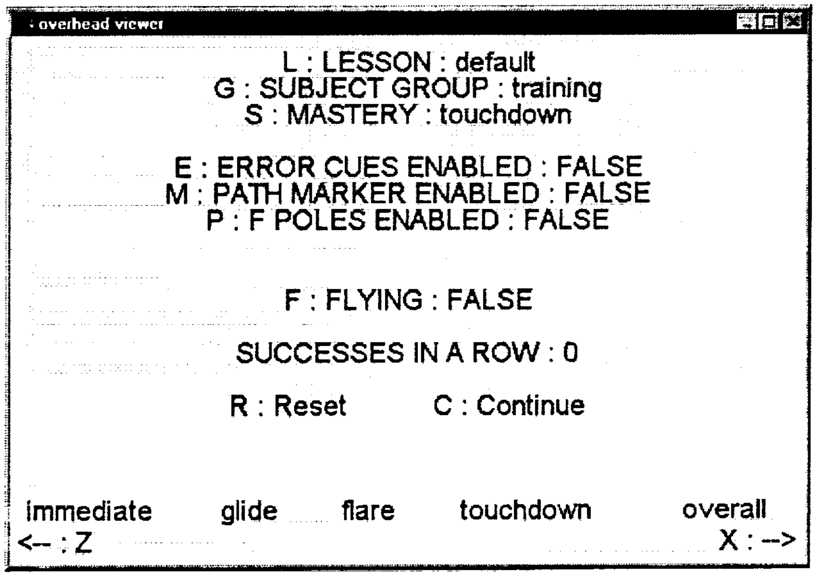

Figure 15. Control and status screen.

Keyboard commands are indicated with the key followed by a colon. For example, to change the SUBJECT GROUP setting, press Shift-G. Note that setting the Caps Lock and pressing the G key will also work. In order to start an autorotation run using the default settings, simply press Shift-R to reset initial conditions and Shift-F to begin flying the maneuver. Remember to click on the window in Figure 15 with the left mouse button to make sure that it has the input focus and will receive keyboard commands. Other optional control mechanisms are described below.

Changing the Lesson. When you press Shift-L from the control and status screen, the system cycles through all available lessons. Lessons are used to establish the initial conditions for the autorotation runs. The following values are obtained from the lesson selected: start location, end location, start altitude, start heading, start pitch, start altitude, wind direction, wind direction variation, wind speed, and wind speed variation. Each of these values is maintained in a set of values for each attribute. For example, wind directions for each lesson are remembered in the "lesson wind direction" set object. By adding or modifying the values in these sets, users can establish desired initial conditions. For detailed instructions, see the PRISMS User's Manual section on "adding a PRISMS object reference to a set" (p. 27).

Changing Subject Group and Mastery. The subject group can be set as either training or control by selecting Shift-G. Training subjects have the ability to review performance metrics and control groups do not. When the subject group is changed, the MASTERY level is automatically changed. When you select the training group, the MASTERY level is set to "immediate." This means that the simulation will terminate at the completion of the immediate response control sequence.

To change the MASTERY level for a training group subject, select Shift-S to cycle through the immediate, glide, flare, and touchdown terminal behaviors. When you select the control group, the MASTERY level is set to overall and the MASTERY level cannot be changed. The overall MASTERY level indicates that the simulation will terminate following the completion of the touchdown maneuver.

Controlling optional training aids. Audio error cues for trim and air speed are enabled and disabled with the Shift-E key. The path marker symbol is enabled and disabled with Shift-M. The F-poles are enabled and disabled with Shift-P. To start and stop the motion of the subject helicopter (toggle the flying state) use the Shift-F key. When motion is "frozen", the active terminal behavior and control position indicators are displayed in preparation for resuming the flight.

Reset and Continue, Shift-R and Shift-C, are both commands that initialize an autorotation sequence. The only difference between the two is that Reset will zero out the number of previous "Successes in a row". Otherwise, both commands will reset all metrics and symbols, initialize the control position indicators, and initialize helicopter attributes in preparation for the subsequent "Fly" command.

Chase View. Figure 16 presents the chase view from the observer viewer. The offset position of the observer is specified in a position attribute of the "experimental control values" object named "observation point offset". The position of the observer is set to the location of the helicopter plus the selected offset.

Immediate Control Sequence Metrics. Notice in Figure 15 that there are two symbols in the lower portion of the screen that look like "← : Z", and "X : →". These symbols indicate keystrokes for switching to either the previous (Shift-Z) or the next (Shift-X) screen. If you select Shift-X from the control status screen you will see the immediate control sequence metrics. Figure 17 presents the immediate control metrics. These same metrics are also shown to training subjects at the conclusion of the selected terminal behavior. On the experimenter's station, however, the screens are presented with an overhead view of the airfield and the student's helicopter. The overhead view is not shown in Figures 18-21 for improved legibility in this printed presentation.

All metric screens present metric symbology in either green or red. If the metric is presented in green, then the measured values are within limits. If the metric is red, then the measured value is outside the specified limits. Most limit thresholds are represented as attributes of the experimenter control values object. If you find some limit that you wish to change that does not already have a limit attribute, simply add an attribute to the experimenter control values and incorporate its use in the corresponding scoring rule.

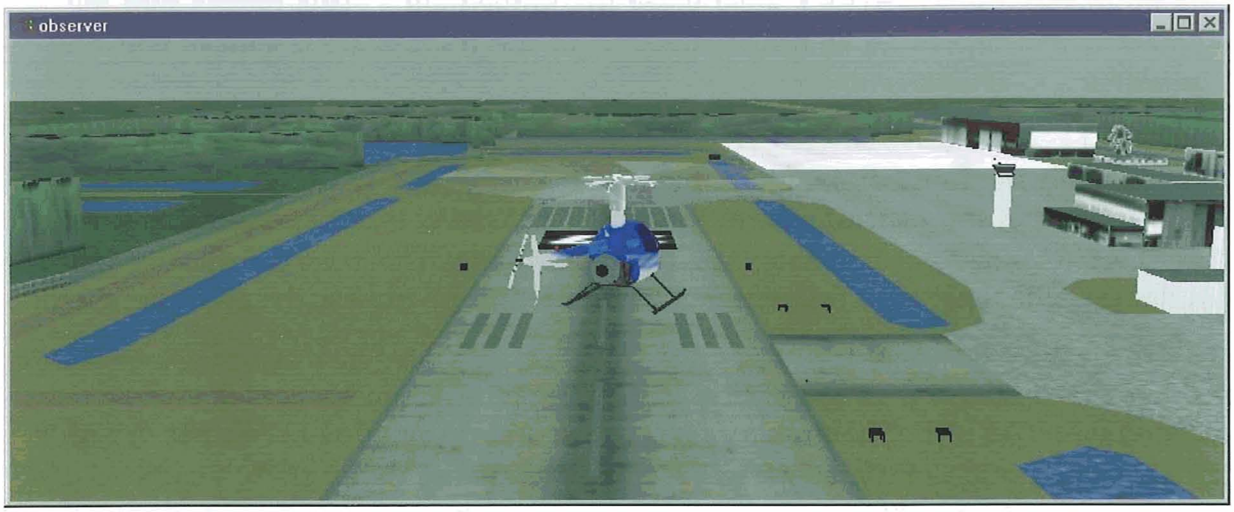

Figure 16. Chase view of the helicopter from the observer viewer.

Figure 17. Immediate control sequence metrics.

Glide Metrics. Pressing Shift-X from the immediate metrics screen takes you to the glide metrics screen. Figure 18 presents the glide metrics as seen from the overhead viewer on the experimenter's station. The same set of metric symbology is available for review by the training subject following the completion of the selected terminal behavior. Note that one RPM deviation is accepted since we are simulating a throttle chop from 85 knots.

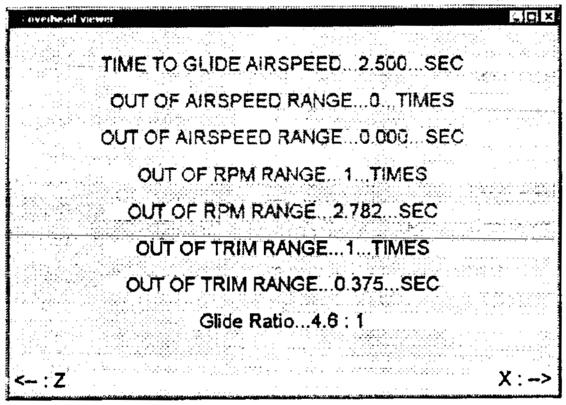

Figure 18. Glide metrics.

Flare Metrics. Pressing Shift-X from the glide metrics screen takes you to the flare metrics screen. Figure 19 presents the flare metrics as seen from the overhead viewer on the experimenter's station. The same set of metric symbology is available for review by the training subject following the completion of the selected terminal behavior.

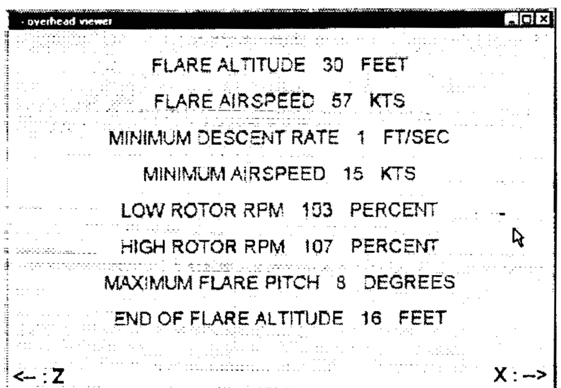

Figure 19. Flare metrics.

Touchdown Metrics. Pressing Shift-X from the flare metrics screen takes you to the touchdown metrics screen. Figure 20 presents the touchdown metrics as seen from the overhead viewer on the experimenter's station. The same set of metric symbology is available for review by the training subject following the completion of the selected terminal behavior.

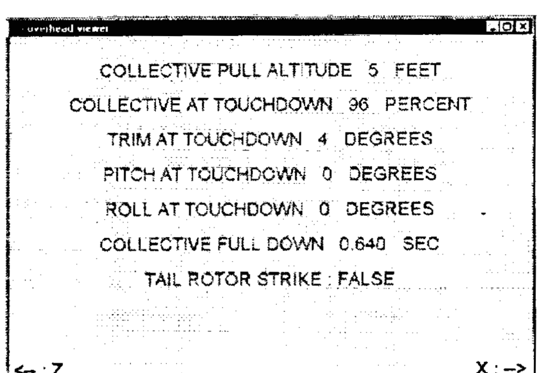

Figure 20. Touchdown metrics.

Overall Metrics. Pressing Shift-X from the touchdown metrics screen takes you to the overall metrics screen. Figure 21 presents the touchdown metrics as seen from the overhead viewer on the experimenter's station. The same set of metric symbology is available for review by both the control and training subject following the completion of the selected terminal behavior.

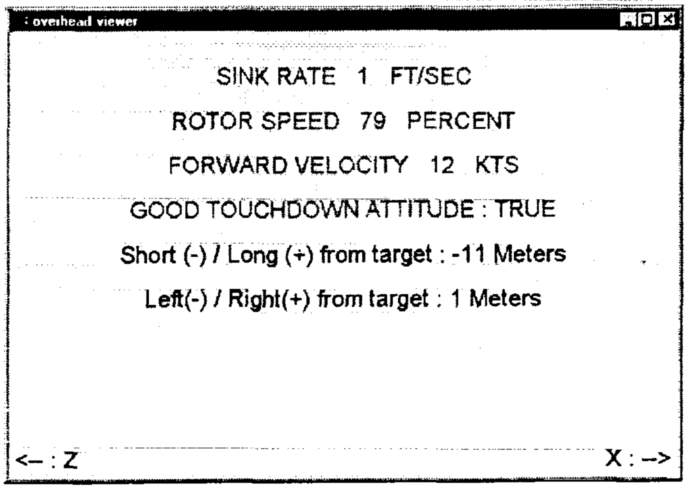

Figure 21. Overall metrics.

Experimental Recording of Performance. Following the completion of a flight, all metric information is recorded in the subject recording file. Figure 22 presents an excerpt from a recording of a training subject. Each line records the value of an attribute in the PRISMS session. The first number is the simulation time and is followed by the object name>attribute name : value for the recorded attribute. Users can easily add new recorded values by modifying the PRISMS session.

The subject recording files are found in the Prisms/Sessions directory under the "Autorotation Trainer" directory. The file name is constructed using the date and time of the start of the session followed by "_sub_rec.txt".

Subject Control of Training Sessions

If the experimenter doesn't need to observe the training, it is possible to allow the subject to control the sessions unattended. Several voice commands and two buttons on the cyclic provide limited control over sequencing through the autorotation training sequences.

Voice Control. The following is a list of recognized phrases and behaviors that can be used by the subject to control the autorotation training session. A push-to-talk (PTT) is implemented on the paddle switch of the cyclic or the experimenter can enable the subject microphone by pushing the microphone button on the DragonDictate voice bar. See PRISMS documentation for additional information.

```
669.703 : experimenter control values>message : ******************************
669.703 : experimenter control values>message : control action : keyboard reset
669.703 : experimenter control values>message : training subject, 0 previous successful,
          terminates at touchdown
897.422 : experimenter control values>message : control action : keyboard fly
925.781 : immediate control sequence metrics>time to collective full down : 0.703000
925.781 : immediate control sequence metrics>time to collective movement : 0.625000
925.781 : immediate control sequence metrics>time to cyclic aft movement : 0.593000
925.781 : immediate control sequence metrics>time to right pedal movement : 0.625000
925.781 : glide metrics>glide ratio : 4.130124
925.781 : glide metrics>out of air speed range count : 0.000000
925.781 : glide metrics>out of rpm range count : 4.000000
925.781 : glide metrics>out of trim range count : 0.000000
925.781 : glide metrics>time out of airspeed range : 0.000000
925.781 : glide metrics>time out of rpm range : 12.484000
925.781 : glide metrics>time out of trim range : 0.000000
925.781 : glide metrics>time to glide airspeed : 9.078000
925.781 : flare metrics>end of flare altitude : 10.868652
925.781 : flare metrics>flare airspeed : 51.075846
925.781 : flare metrics>flare altitude : 22.384766
925.781 : flare metrics>high rotor rpm : 1.078537
925.781 : flare metrics>low rotor rpm : 1.043840
925.781 : flare metrics>maximum flare pitch : 24.530485
925.781 : flare metrics>minimum airspeed : 34.866661
925.781 : flare metrics>minimum descent rate : 26.129944
925.781 : touchdown metrics>collective at touchdown : 0.961060
925.781 : touchdown metrics>collective pull altitude : 10.868652
925.781 : touchdown metrics>forward velocity at touchdown : 22.394359
925.781 : touchdown metrics>overall attitude at touchdown : TRUE
925.781 : touchdown metrics>pitch attitude at touchdown : 0.238744
925.781 : touchdown metrics>roll attitude at touchdown : 0.000000
925.781 : touchdown metrics>rotor speed at touchdown : 0.695845
925.781 : touchdown metrics>sink rate at touchdown : 10.756878
925.781 : touchdown metrics>tail rotor strike : FALSE
925.781 : touchdown metrics>time to collective full down : 1.329000
925.781 : touchdown metrics>trim at touchdown : 1.048292
925.875 : experimenter control values>message : control action : automatic termination at
          touchdown
925.984 : experimenter control values>immediate control sequence successful : TRUE
925.984 : experimenter control values>glide performance successful : FALSE
925.984 : experimenter control values>flare performance successful : FALSE
925.984 : experimenter control values>touchdown performance successful : TRUE
925.984 : experimenter control values>overall performance successful : FALSE
```

Figure 22. Excerpt from subject recording file.

1. "Calibrate Head Tracker" – This causes the subject process to calibrate the head tracking sensor.
2. "Reset" – Prepare for a new subject by zeroing out the previous number of "successes in a row" and initializing all helicopter and metric attributes.
3. "Continue" – Same as Reset except do not change "successes in a row".
4. "Fly" – Start the helicopter motion after either a "freeze", "reset", or "continue" command.
5. "Freeze" – Stop the helicopter motion and remember the current control positions in the control position indicator symbols.
6. "Engine start" – At any time, this restores the power available so that you can fly away. This is not an official part of any training sequence.

The response of the PTT is not very reliable due to an operating system related process swapping problem. To avoid this difficulty, leave the microphone turned on as described above.

Metrics Review. At the conclusion of a terminal behavior, the appropriate metrics screen is brought up in the pilots HMD. Training subjects are permitted to scroll back and forth through the various metric screens using the Dome switch on the cyclic. This is the same switch that was previously used to switch between symbol modes on the Apache IHADSS symbol set. It is found directly below the red button on the cyclic.

Pushing up on the switch scroll forward through the metric screens in the same fashion as the Shift-X key from the overhead viewer on the experimenter's station. Pushing down on the switch scrolls backward through the metric screens.

Only training subjects are permitted to review results in this fashion. Control subjects are only given the overall metrics and cannot scroll through metric screens.

Section 6. Basic Instructional Sequence

The instructional sequence described in this section assumes that the students are already skilled in the R22 helicopter. The specific number of flight hours, or whether they are already licensed in the aircraft would probably not lead to changes in the overall course of instruction. The instructor, however, might chose to emphasize some parts of the learning sequence based upon student strengths and weaknesses.

The PRISMS Autorotation Trainer is not currently designed for fully automatic training and depends, at least initially, on the instructor for specific descriptions of the autorotation, observation of the student's performance, and guidance in effective control usage patterns. Once the student's skills have developed sufficiently, practice may be undertaken without the instructor's presence, using the performance measurement and feedback features of the system. The steps in the basic instructional sequence are described below.

Review of the Full-Down Autorotation

The instructor will discuss autorotation with the student, first determining the student's level of expertise in the hovering autorotation and the power-recovery autorotation and then describing how the full-down, straight-in autorotation is to be performed. The instructor will provide an overview of the four stages of the autorotation:

1. Perform immediate autorotation control sequence
2. Establish normal glide
3. Perform the flare
4. Manage soft touchdown

The instructor will then discuss the skills required for successful completion of each stage. The instructor will also provide reviews of each stage and the required skills as the student's training progresses.

Initial Introduction to the PRISMS Simulator

The instructor will next describe the PRISMS simulator's characteristics and capabilities to the student. The basic training session scenario will be described, and the various metrics that the training system provides will be discussed. The student will then enter the simulator, observe the control locations and movements, and don the HMD. With the instructor's help, the head tracker will be calibrated and the student permitted to perform a brief test flight for familiarization with the simulator's flight handling qualities. The instructor will point out the rotor rpm and airspeed gauges and the trim strings.

Beginning the Training Sessions

The instructor will describe the basic training session for the first stage of the autorotation: Perform immediate autorotation control sequence. In brief, the basic session begins at 500 feet, in level flight at 85 knots flying over an airport. After a few seconds (varied unsystematically between trials), engine power is suddenly lost and the engine sound stops. The pilot is to perform the appropriate control sequence preparatory to a straight-in autorotation to the airfield.

Training Session Stage Linking

Training sessions begin with just the first stage; Perform immediate autorotation control sequence. Only after that stage is mastered is the next one added to the session (Establish normal glide). The same process is followed until all four stages are performed together. Until mastery is achieved, the session will end at the conclusion of the stage with a screen describing the pilot's performance and any errors or other out-of-criteria events. The instructor may then discuss any observed problems and their solutions and then initiate a new session. During "solo" practice, a student can begin a new trial with a voice command.

Mastery is considered to have occurred when the stage is completed within the acceptable performance criteria three times in a row. When the pilot is considered to have mastered the stage, the subsequent sessions will not stop at the end of the mastered stage (even if there are errors) but continue into the next stage. An advisory screen at the start of each trial will indicate the stages to be performed (e.g., "Immediate response, normal glide, and flare."

Employment of Basic Instructional Support Features

The PRISMS Autorotation Trainer is equipped with a number of special training aids called "Instructional Support Features," or ISFs that may be employed by the instructor, as desired. Specifically, the instructor may elect to "freeze" the problem and discuss the student's performance, present the augmented visual aids (F-poles and/or flight path marker), or introduce automated auditory error cueing Because there is little experimental data suggesting just how these ISFs might best be employed, it is logical to permit the instructor to use his best judgement in their application.

However, it is suggested that the F-poles be presented to the student early in the second stage (Establish normal glide) with an explanation of their proper employment. At the instructor's option, the flight path marker may be added to clarify the aircraft's projected vector. The instructor should subsequently withdraw these aids and establish that the student can perform the normal glide without them. Either or both of the aids may be briefly reintroduced during mastery of the flare.

Employment of Advanced Features: Initial Condition Sets

In order to simplify the training process by focusing on the basic skills, the simulator was originally designed to train a basic, straight-in landing to a broad open field. For initial autorotation training, this approach is still the most appropriate method. However, in the real world the available landing area often will not be so large, and will require that the pilot adapt his maneuvers to touch down on a specific, desirable spot. An ideal spot, of course, is one that is level, hard-surfaced, uncluttered by obstacles, and large enough to permit some slide after touchdown.

It is quite likely that the best spot for a landing will not be directly in front of the aircraft, at the end of normal glide path. The ideal spot may well be nearer or farther from the aircraft than would be reached by the normal glide path. In addition, it may be well off to one side, or even behind the aircraft. Too make matters much more complicated, the wind speed and direction have a powerful influence on whether specific spots can be reached, and what maneuvers are necessary in order to permit reaching the spot, flaring into the wind, and performing a soft touchdown.

Because of the tremendous array of possible situations, the training system must rely heavily on the instructor for presentation of instructional strategies and environmental conditions. Nevertheless, recent additions to the training system now permit the instructor to move far beyond the relatively simple straight-in landing and create an unlimited range of emergency situations. Creating additional initial condition sets, or "lessons," as described in Section 5, and detailed in the PRISMS User's Manual (p. 27) can provide the instructor with a powerful set of instructional tools. The instructor can identify the desired engine-out position, altitude, airspeed and heading as well as the target landing position. Furthermore, the wind speed, and direction can be entered, and all of these variables saved for immediate recall during subsequent instructional periods.

Thus, the instructor can prepare lessons for dealing with an unlimited variety of different wind conditions and distances and directions to the target landing spot. He may then guide the student through a variety of S-turns, 180° turns, 360° turns and other maneuvers necessary for dealing with the situations thus created.

Section 7. Suggestions for System Evaluation

There are three primary methods for evaluation of the flight simulators. The first is that of cost-benefit analysis, examining the expenses saved by using a simulator system, compared to instruction in a real aircraft. The second is an experimental method constructed to demonstrate and measure the student's performance improvement based upon simulator use. The third is that of pilot ratings of the simulator. All of these methods will be described in this section, and specific suggestions offered for evaluating the PRISMS Autorotation Trainer.

Cost-Benefit Analysis of the PRISMS Autorotation Trainer

The benefits of the PRISMS Autorotation Trainer are abundantly obvious. First of all, as described earlier in this report, using an actual aircraft to instruct full autorotation to the ground is far too dangerous and too likely to damage the aircraft. A simulator completely eliminates the dangerous and extremely expensive incidents that occur in a real aircraft. It is noteworthy that a simulator also eliminates or greatly reduces the student's fear of an accident, permitting the student to concentrate on correct control inputs while still experiencing a realistic autorotation experience. Because the hovering autorotation and power-recovery autorotations currently practiced in the aircraft are in some ways very different from the full-down autorotations required in an emergency, the simulated autorotation is in some ways more realistic than the currently practiced partial autorotations.

However, assuming for the moment that fixed-base operators would permit the practice of full-down autorotations in their aircraft, and that some miraculous method were found to prevent accidents, the PRISMS Autorotation Trainer would still be superior on a cost basis. The key issues are the number of autorotations that could be performed per unit time and the cost of that time. In the R22, at an isolated area (no airport traffic and regulations) an expert could do up to 15 autorotations per hour, and a student could probably do 8-10 per hour. In contrast, in the PRISMS Autorotation Trainer a student could begin a new session with a button press and could perform about one autorotation per minute, or 60 per hour.

Finally, the costs of practice in an aircraft versus a simulator must be considered. Assuming the student has actually purchased an R22 helicopter, the hourly costs of flight can be determined by figures available directly from the Robinson web site. The Table 2, below shows flight hour costs figured over a two-year time period and a four-year time period ($62.40 or $68.70, respectively).

When the cost of an instructor is added, the hourly fee increases to $87.40 or $93.70. These figures are rather optimistic because most students would not own a helicopter, but would have to rent the aircraft at the going rate of $130.00 per hour. With an instructor the total is $155 per hour, or about $15.50 per autorotation

The expense of flight in the PRISMS simulator is essentially the cost of electricity – about 12 cents per hour. Initially, an instructor would be needed so the cost would be about $25.00 per hour, or about $0.42 per autorotation. Once the student could practice without need for an instructor, the price would drop to less than one cent per autorotation. Because hundreds of autorotations must be practiced for true mastery of the maneuver and its variations, the difference between $15.50 and $0.01 per maneuver becomes extremely significant.

Table 2. R22 Flight Hour Costs.

Cost for 2000 hours of Flight in R22	
(Over two years time period)	
Hull & Liability Insurance	$12,600
Reserve for Overhaul	$65,000
Direct Operating Cost	$47,200
Total Operating Cost	$124,800
Total Operating Cost/Hr	$62.40
Instructor/Hour	$25.00
Total per Hour	$87.40

Cost for 2000 hours of Flight in R22	
(Over four years time period)	
Hull & Liability Insurance	$25,200
Reserve for Overhaul	$65,000
Direct Operating Cost	$47,200
Total Operating Cost	$137,400
Total Operating Cost/Hr	$68.70
Instructor/Hour	$25
Total per Hour	$93.70

The Problems of Evaluating Flight Training Devices by Experiments and Ratings

There have traditionally been two primary ways of evaluating the training value of a flight simulator: the transfer experiment, and the rating method. The transfer experiment requires that the student practice in the simulator and then be tested in the actual aircraft to demonstrate the transfer-of-training effect. In contrast, the rating method requires that pilots experienced in the actual aircraft rate the simulator in accordance with its perceived similarity to the aircraft. It is assumed that high similarity ratings assure high training value of the simulator.

Hundreds of millions of dollars have been spent on procurement of flight simulators without transfer experiments having been performed to justify these expenditures, primarily because the cost of these experiments is so high. Furthermore, it is generally argued that even low levels of transfer are acceptable in simulators since they are safer, better designed for measuring performance, available in all weather, and in the long run, much less expensive than training in the actual aircraft. For example, although the Army flight simulators are relatively expensive to operate, their costs do not approach the approximately $4,300 per hour expense of flying an Apache helicopter (not including weapons costs).

Some years ago, Adams (1979) argued that the transfer experiment methodology was basically unsuitable for use with aircraft. The difficulty is in the matching of the prior experience of the experimental (transfer) group and the control group (which does not receive simulator training). The control group members must somehow achieve some minimum level of flying skill in the aircraft so that they can fly it well enough to generate meaningful performance measures. However, any additional proficiency (beyond the minimal level) achieved by the control group subjects will obscure the training capabilities of the simulator. Furthermore, the experimental group must be trained well enough to be allowed to fly the actual aircraft on the first try after the training, so that transfer is essentially guaranteed in advance. As Adams put it, "it is a strange experiment where positive outcome is a precondition."

Another type of transfer experiment is that of "backward" transfer, or aircraft-to-simulator transfer. In this paradigm, expert pilots in a given aircraft perform standard aviation tasks in the aircraft simulator without any prior practice in the simulator. For example, Kaempf, Cross, and Blackwell (1989) evaluated backward transfer on the AH-1 Flight Weapons Simulator (FWS) and found that the experienced instructor pilots received unsatisfactory performance ratings on 82% of the emergency touchdown maneuvers performed in the simulator, even though they had recently passed checkrides employing these maneuvers in their aircraft. As a result, the FWS was deemed unsuitable for training emergency touchdown maneuvers.

A more recent example of the backward transfer paradigm is that evaluating the effectiveness of the Simulator Training Research Advanced Testbed for Aviation (STRATA) as an AH-64 training simulator (Stewart, 1994). Ten expert AH-64 pilots performed 13 Aircrew Training Manual (ATM) tasks in the STRATA and were rated in real-time by a Standardization Instructor Pilot (SIP). Of the 130 ATM task events, 88.5% were performed to ATM standards, strongly suggesting that STRATA is a valid simulation of the AH-64 helicopter. In addition, most participants rated STRATA as highly similar to the AH-64 in handling characteristics.

The question remains whether similarity of the simulator and the aircraft, either demonstrated from backward transfer or by pilot ratings, is the most appropriate method of determining the utility of a training simulator. Adams (1979), for example, has challenged the assumption that the amount of transfer of training is positively related to the similarity between the simulator and the aircraft, pointing out examples of positive transfer from very low-fidelity simulators. Furthermore, he found a series of faults with the use of the rating method. For example, Adams questioned the pilots' ability to objectively discern similarity, given that similarity is a psychological dimension and its rating varies with the pilot's personal experience. Most persuasively, Adams stated that the rating method is based on an incorrect syllogism:

Pilot ratings are useful for evaluating aircraft

A flight simulator is an earthbound aircraft

Therefore pilot ratings are useful for evaluating flight simulators.

The error, he points out, is in the premise "A flight simulator is an earthbound aircraft." Instead, the premise should read "A flight simulator is a teaching machine," in which case the conclusion does not follow.

As an alternative to transfer of training and rating methods for determining the utility of flight trainers, Adams suggests that modern simulators be judged according to the extent to which they employ five major principles.

(1) The first and foremost principle is that human learning is dependent upon *knowledge of results*.

(2) The second principle is *perceptual learning*, which is an increase in the ability to extract information from stimulus patterns as a result of experience.

(3) The third principle is *stimulus-response learning*; learning to do something such as control movements in the presence of system stimuli.

(4) The fourth principle is that transfer of training is the highest when similarity of the training and transfer situations is the highest.

(5) The fifth principle is that a trainee must be motivated, and that the characteristics of the task are a source of motivation.

Adams states that "the reason for putting forth these principles is *the assertion that a system built on sound scientific laws needs less concern with evaluation because a good scientific law produces accurate prediction, and when the outcome can be predicted it is redundant to conduct an evaluation.*"

There is yet another problem with using backward transfer for evaluating an autorotation trainer. To employ the backward transfer method, it is critical that the pilots perform standard aviation tasks (such as ADS-33 tasks) in the simulator. However, expert helicopter pilots perform the autorotation maneuver in many different ways and there is simply no standard technique for achieving a successful autorotation. Although we recognize that there are many ways for experienced pilots to perform the maneuver, we believe the training and testing should be conducted initially using a single "school solution" autorotation maneuver with PRISMS so that training aids and performance metrics may be applied. Unfortunately, measurements of performance based on such a school solution would not necessarily be applicable to the variety of methods employed by expert pilots, so that backward transfer could not be effectively measured. It would still be possible to gather pilot ratings of similarity of the simulator to the R22 but, as Adams has pointed out, these ratings are not necessarily indicative of the transfer of training attributable to use of the simulator.

A Proposed Approach for PRISMS Autorotation Trainer Evaluation

Our suggested approach is as follows: Instead of the naïve test subjects that would be used in a forward transfer study, it would make sense to use qualified R22 pilots who have been trained in the standard way in the aircraft, but have never done a full-down autorotation. First, a preliminary survey would be administered to the pilots to determine their helicopter flight hours, number of power-recovery autorotations and hovering autorotations and other pertinent data.

Next, the pilots would be given a brief PRISMS familiarization flight and then told to perform a series of full-down autorotations meeting the school solution specifications. Based on their performance, the pilots would then be divided into two groups for further training. One of the groups would be taught with all of the PRISMS metrics, feedback provisions, and instructional aids. The other group would simply practice on PRISMS with no special aids except the metrics indicating the overall success of the touchdown. Performance data would be gathered continuously for both groups for comparisons and plotting of learning curves over the course of the experiment.

Training would continue over a predetermined number of sessions. The resulting data from each subject, when compared to the autorotation performance baseline established during the familiarization flight, would show the speed and magnitude of improvement in autorotation skills based upon practice with the PRISMS simulator. In addition the differences between the data of the two groups would show the extent to which the instructional support features augmented the students' learning rate as opposed to practice alone. Both types of data would provide very useful knowledge directly applicable to the ability of typical pilots to perform a full-down autorotation as well as an indication of the techniques necessary for improving their skills.

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