RECENT DEVELOPMENTS IN INTELLIGENT AUTONOMY FOR VTOL UAVS[1]

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Abstract

In 2003 the AHSI established a permanent technical committee to encourage the development of *Intelligent Autonomy (IA) for VTOL UAVs.* IA represents a fundamentally new market sector for both uninhabited and inhabited (manned) rotary wing aircraft. One definition of IA is: *The ability of the combined operator / machine system to appropriately choose the level of operator involvement for a given task, and modify that level as necessary during the execution of the task.* The paper provides a survey of recent flight demonstrations that are leading the development of this new and powerful technology.

Introduction

The paper presents a vision for the future of Intelligent Autonomy (IA) incorporated in VTOL UAVs. A revolution is occurring due to the rapidly evolving synergism between fundamental advances in the understanding of intelligent behavior, the exponential growth of low cost computing, and the availability of wide spectrum sensing and imaging capabilities. This synergism will significantly alter the outlook for the future of VTOL and rotary wing aircraft – both inhabited and uninhabited, and will engender powerful new market forces while enabling entirely new concepts of military operations.

Figure 1 Intelligent Autonomy (IA) applies to the entire spectrum of UAVs

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Five Focus Areas for the AHS International

The AHS International Uninhabited VTOL Aerial Vehicle Technical Committee is attempting to monitor the diverse activities in this exciting field by addressing five different focus areas:

1.   Intelligent autonomy (of individual vehicles): intelligent interfaces to human operators; autonomous operations and control (including obstacle avoidance); architectures for autonomy; solution of core theoretical issues in perception, learning and decision processes with pragmatic operational constraints.

2.   Multiple-UAV data collection and fusion (technologies): autonomous / semi-autonomous sensor operation; sensor data registration and exploitation; data communications sensors and protocols; multi-source data integration and exploitation; distributed sensor systems for multi-aspect information generation.

3.   Collaborative planning and control for UAVs: collaborative control for manned / unmanned systems and non-homogenous UAV types; airspace management and deconfliction; joint planning and execution; architectures for collaboration; and multi-vehicle command and control

4   Applications of Intelligent Autonomy to reduced accident rates of inhabited and uninhabited systems: IA enables new and improved safety capabilities for rotorcraft. For example, it may be possible to substantially reduce or even eliminate the classical height-velocity restriction. The synergism of improved sensors and IA can potentially reduce the accident rates due to controlled flight into terrain. IA applications of Robust Control Theory can enable dynamic reconfiguration of controls in response to actuator/control system failures.

5.   Metrics for Intelligent Autonomous systems: In order to characterize the level of intelligent autonomy of UAVs, the AHSI UAV committee has adopted metrics proposed by the U.S. government ad hoc committee on Autonomy Levels For Unmanned Systems (ALFUS). The ALFUS scale is defined by a three-parameter vector, which includes (i) the level of human interaction (computational hierarchy), (ii) the level of mission complexity (number and types of decision executions and effectors), and (iii) the level of environmental difficulty. (iii) the level of environmental complexity / threat. The scale is useful in that scientists, engineers, operators and program decision makers can readily interpret it for different purposes.

This Paper

This paper discusses the unique domain of application for VTOL and rotary wing platforms equipped with functional IA and highlights some recent IA flight-test accomplishments. Achievements are described in the six major IA categories of Planning, Sensing, Perception, Understanding, Deciding and Acting. While significant advances have been made in the Planning, Sensing and Acting domains, the key enabling areas of Perception, Understanding and Deciding are still in their infancy. Nevertheless it will be shown that critical research outside the rotorcraft community is now opening up the future in the latter areas, and it is simply a matter of time before rotorcraft will begin to assimilate these emerging technologies. New IA attributes such as "situational understanding", "selective learning" and "inquisitiveness / curiosity" are beginning to enter the VTOL UAV field.

How are VTOL UAVs Unique?

The ability to takeoff and land vertically and to hover and maneuver in all axes at low speeds provides some unique *operational attributes* for VTOL UAVs – relative to fixed wing types of UAVs:

- *Airfield Independent –* vertical takeoff and landing from unprepared sites is a tremendous mobility and response time advantage
- *Maneuverable in Restricted Areas –* a necessity for effective air-ground operations in urban areas, forested areas and steep terrain
- *Responsive –* rapid repositioning to gain tactical advantage
- *Intrusive –* under-weather search, classification, identification
- *Precision Hover –* enables unique staring sensors and zero ground speed sensors for event monitoring, actionable identification & low false alarm rates for camouflaged, concealed and deception conditions
- *Persistence –* omnipresent in time & space
- *Monitoring –* reconstruction of events in time & space
- *Ground Loiter Capability –* an endurance extender that can double as a ground sensor
- *Distributed Platforms –* multiple perspectives aid search, classification, identification, targeting
- *Collaborative Systems –* real-time sharing of sensor data between platforms and onboard fusion enables new levels of semi-autonomous situational awareness and increased intelligence of operations
- *Cost Effective –* favorable cost-exchange ratio under many scenarios
- *Scalable –* these attributes apply to all sizes of UAVs from large tilt rotors to micros

VTOL UAVs Enable a New Paradigm

By utilizing the unique operational attributes combined with advanced sensors and IA, the VTOL UAV enables the operator to maintain dominant awareness in space and time. He is no longer constrained by the necessity to *react* to fleeting targets with 'time sensitive targeting (TST)'. In fact, this is a fundamentally new paradigm to be characterized as "MTEB":

"MTEB: Monitoring the Time Evolution of the Battlespace in order to provide the operator with the capability to select the time and location of action"

The chart below illustrates an example of the MTEB paradigm. In this scenario, eight UAV helicopters are equipped with advanced foliage penetration GMTI radars, which are capable of detecting personnel moving under forested and obscured visibility conditions. The UAVs must maintain essentially zero ground speed in order for the radar to operate effectively, and they must point into the relative wind for wind speeds above about 30 knots. In this situation, the UAVs work collaboratively, sharing detection and track data, to continuously monitor the battlespace for movements. The operator may then incorporate other information to determine possible intent and disposition of the dismounts and then select the optimal course of action.
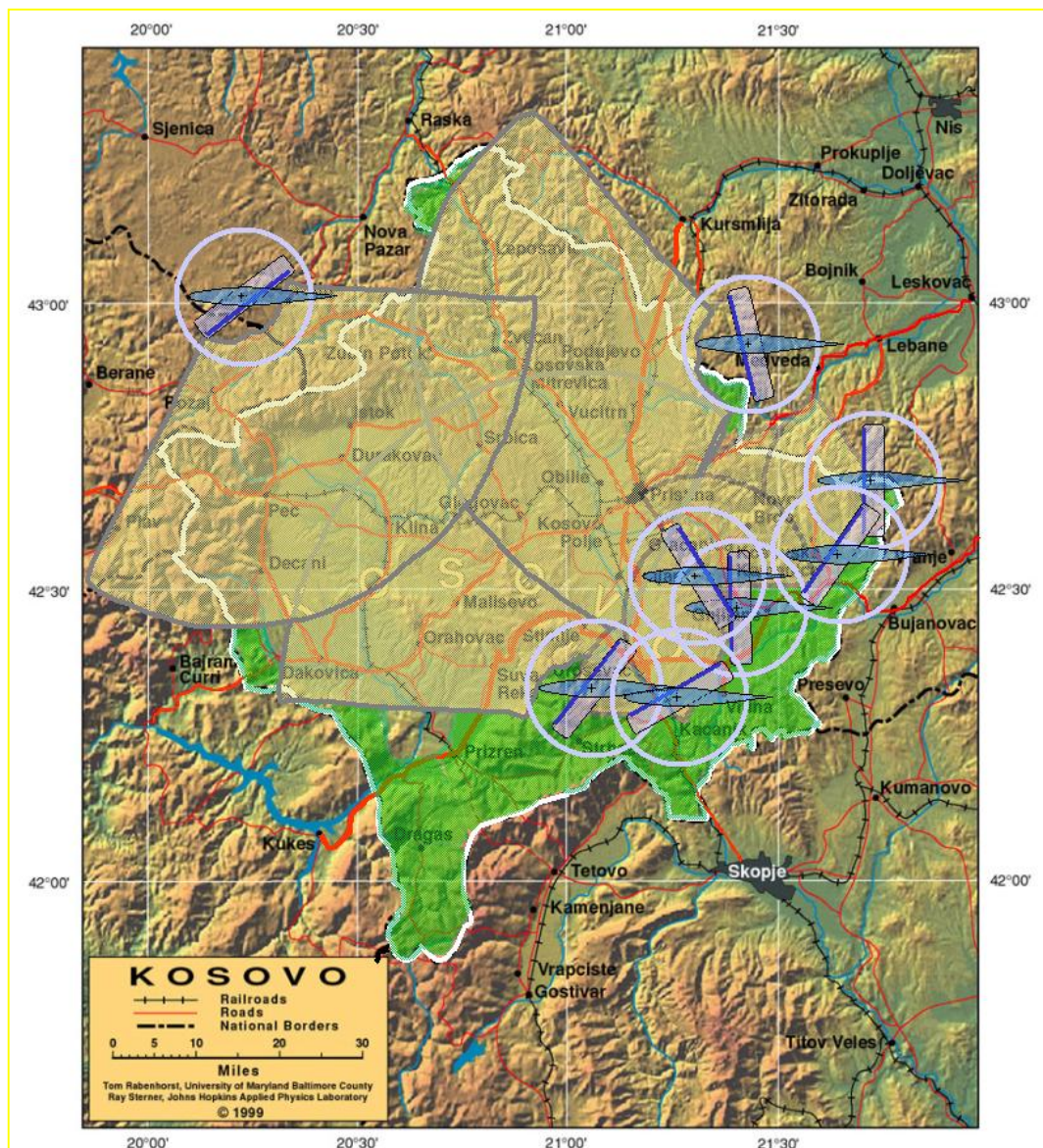
Figure 2 MTEB - Monitoring the Time Evolution of the Battlespace - A New Paradigm Enabled by Intelligent Collaborative Autonomy

UAV Attributes Required for Future Operations

Core UAV attributes include performance, reliability and robustness, sensors and communications, susceptibility and survivability features, and IA. The latest generation of UAVs has employed simple autonomy using autopilot and GPS type functions. In the future, increasing levels of IA will be employed in order to increasingly reduce the level of human-machine interface required and the numbers of UAVs that can be managed by an operator. With the advent of networked communications, IA will be able to manage multi-platform operations and multi-platform information fusion on behalf of the operator. Many missions will be conducted autonomously with operator involvement on a 'by exception' basis. Furthermore, IA will also be able to improve the core UAV capabilities in all of the areas shown.
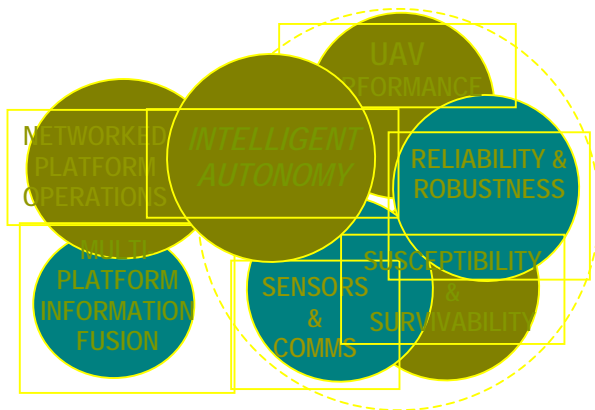
Fig 3 UAV Attributes Required for Future Operational Capabilities

Reliability and Robustness: First Things First…

Current UAV reliability is unacceptably low: the rate of Class-A non-combatant mishaps UAVs varies from over 300 per 100,000 flight hours to as low as 32[3]. The associated replacement / repair cost varies from $1500 to over $5000 per flight hour. These rates are for fixed wing designs, UAV *helicopters* do not yet have sufficient flight hours to support useful statistics, but some insight can be obtained from manned helicopters. For example, in the case of military light observation helicopters such as the OH-58D, the comparable Class-A

mishap rates average 2.9 per 100,000 flight hours[4]. While this is low compared with UAVs, it is over twice the rate for other tactical aircraft. An analysis of the causative factors for the high UAV and tactical helicopter loss rates is summarized below:

Causes of RQ-1, RQ-2 and RQ-5 Fixed Wing UAV Class A Mishaps

- **17% human operator / ground control system**
- **26% flight control system**
- **11% communications / data link**
- **37% power / propulsion**
- **9% miscellaneous causes**

Causes of OH-58D Manned Helicopter Class A Mishaps

- **47% CFIT (Controlled Flight Into Terrain)**
- **3% mid-air**
- **20% taxi, take off, landing**
- **16% power/fuel**
- **14% system/other**

The causal factor in 67% of the manned helicopter cases involved a *"lack of effective aircrew coordination"*, while 54% of the UAV cases involved a combination of human and control/data link causes. Rotary wing UAVs operating in proximity to the ground must address *both* domains if they are to achieve broader use and acceptance. It is here that IA can contribute.

IA - Making UAVs indispensable

The projected global market for UAVs over the next 10 years exceeds $35B[5]. However, this projection does not include the tremendous capabilities enabled by Intelligent Autonomy, which is riding its own engine of change – a parallel expansion in the field of artificial intelligence that is projected to exceed $25B *per year* by 2010.

But what do we mean by IA? How is it quantified?

To answer the first question, the VTOL UAV committee has adopted the following definition:

Intelligent Autonomy (IA): "The ability of the combined operator and machine system to appropriately choose the

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[3] *Unmanned Aerial Vehicles Roadmap*, Dec 2002. Class-A mishaps result in loss/ damage over $1M. UAV rates contrast sharply with manned tactical military aircraft Class-A mishap rates of 1.0 to 1.5.

[4] Committee on Armed Services Hearing on Military Aviation Safety, 11 February 2004
[5] The Teal Group, Arlington, Virginia USA

level of operator involvement for a given task, and modify that level as necessary during execution of the task"

Thus, IA involves the optimal combination of operator and machine, or *Human-Robotic Interface* (HRI), needed to execute a given task. The objective in general is to minimize the extent of operator involvement, reserving it for only the higher perception and cognition needs of the mission, and thereby minimizing the cost and maximizing the operational effectiveness of the system. The task(s) referred to in the definition involve the entire spectrum of *mission complexity* in *varying environments*.

The answer to the second question is more complex and has been addressed by an ad hoc group of specialists under the auspices of the U.S. National Institute of Standards and Technology (NIST)[6]. After reviewing the various autonomy developments in UGVs, UAVs and UUVs the group has adopted a technical measure of IA that enables the further development of quantitative metrics. The new measure is denoted **Autonomy Levels For Unmanned Systems** (ALFUS) and contains the three principle attributes of IA on each orthogonal axis as shown below.
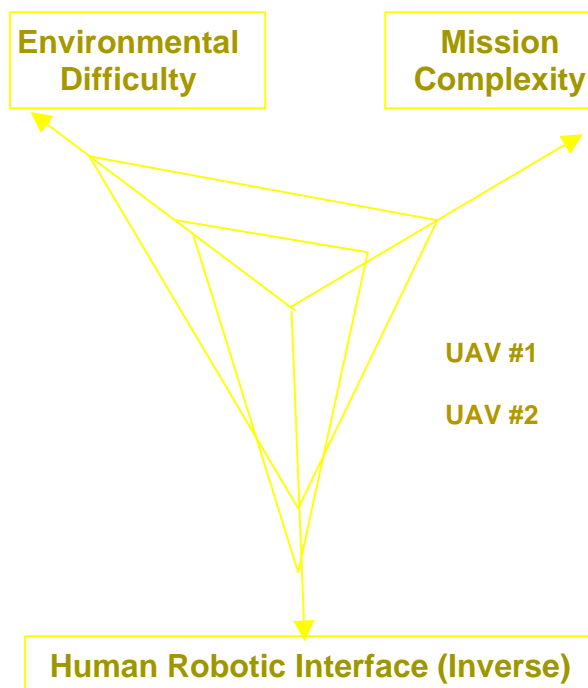
Figure 4 Autonomy Levels For Unmanned Systems

6 **www.isd.mel.nist.gov**

Environmental Difficulty Metrics
Environments for UAVs are similar to manned aircraft and may contain one or more of the following:
- Instrument meteorological conditions
- Natural and man-made obstacles
- Threats, including weapons and interference
- Difficulty of observation (camouflage and concealment environment)

Human Robotic Interface Metrics
HRI is an emerging area and the metrics are evolving. However, a considerable amount of data has been acquired from thousands of hours of current UAV operations. The elements of current HRI (without AI) include the following:
- Operator & Support Skill Levels
  - Extent of training & education
  - Complexity of control station
  - Logistic support effort
  - Communications complexity
- Operator Workload:
  - Physical effort
  - Mental effort / frustration
  - Temporal performance
- Unplanned Human Interventions
  - Number, frequency & duration
- UAV to Operator Ratio

Mission Complexity Metrics
The mission complexity involves six key elements shown below which also interact with the environment and human operator. The level of mission complexity also involves the number of disparate tasks and the degree of abstraction involved between the HRI, the environment and the tasks.
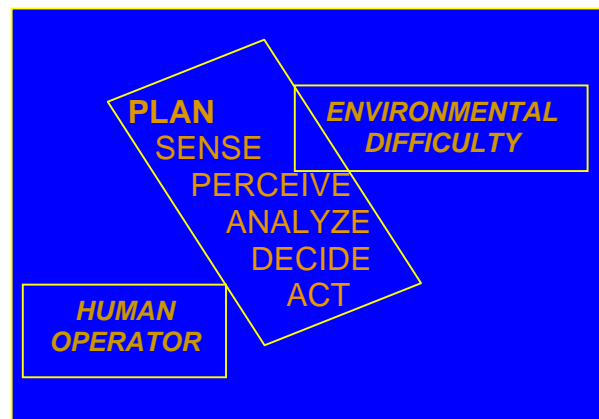
**Figure 5 The 6 Key Elements of Mission Complexity**

As an example, consider the operator command *"proceed to sector 3 and search for armed individuals".* This statement implies a very high level of HRI that triggers multiple paradigms:

- **Plan** the mission taking into account various prioritized mission objectives, environmental factors, geography / terrain, the capabilities of the particular UAV (such as sensors, maneuver ability, performance (range-payload-endurance-altitude-speed), and other parameters. In the example, this would entail creating a route plan to avoid obstacles and threats and a sensor employment plan to conduct the search at the appropriate altitude and standoff distances and within the available fuel of the platform. In the case of previously unanticipated events (change in weather, 'pop-up' threats or obstacles, etc.) the air vehicle would reroute as needed to achieve the mission goals at the minimum 'cost' in terms of time, fuel burn or other optimization parameters.
- **Act** or execute the mission according to the plan, In the example, this would entail all of the steps for preflight check out, takeoff, fly out, sensor employment, maneuver, data collection, etc. Changes to the plan or exceptions for unanticipated events may cause extreme maneuvers, which must be limited according to loads, accelerations or other constraints on platform dynamics.
- **Sense** both the external situation and the internal states of the UAV using a number of active and passive sensors and, in the case of cooperative operations, sensing the communications and data streams from other

recognition of objects, environments, signals of UAVs and transmitting own-self data.
- **Perceive** what the sensors are observing, turning raw signals and imagery into interest and other external and internal situations – in effect creating an artificial model of the world in the UAV's IA processor. In the case of cooperative operations, also fusing the data and imagery to increase situational awareness and perception of the environment, objects, and states of other platforms.
- **Analyze** the perceptions to name objects, order their importance, locate them in space and time, and generally 'understand' the external situation – in effect, creating an internal model of the real world in the IA processor of the UAV.
- **Decide** based upon the analyzed perceptions to come up with new courses of action that may differ from the plan. The decision process is both reactive (i.e., immediate response to environmental changes such as obstacles) and deliberative (i.e., longer-duration processing of changing mission priorities and new plan options based upon environmental or HRI analysis). Decisions of course cause the entire cycle to repeat leading to new Actions.

As shown below, UAVs are just beginning to 'climb' the ALFUS scale. The figure characterizes the trend in HRI with the level of Mission Complexity described above for benign environmental conditions. Green represents achievements to date, orange represents current flight demonstration plans and red defines simulated capabilities.
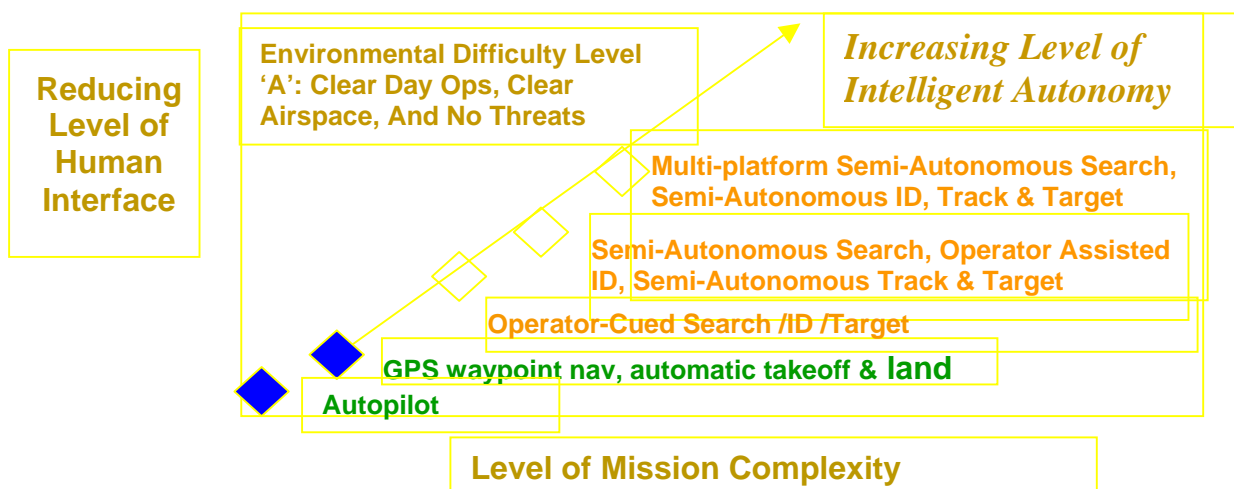

Figure 6 Where are UAVs on the Autonomy Levels For Unmanned Systems Scale?

Architectures for IA

Procedural Reasoning System[7]: A variety of intelligent autonomy architectures have been developed and implemented to varying levels. A classical ground robotics architecture is the Procedural Reasoning System (PRS) from SRI, Menlo, California. A high-level diagram of PRS is shown below and consists of the following elements:

- **World** represents the real world environment that the PRS seeks to understand
- The **interpreter** is the internal model of the world created by PRS using a world **data base** (for example digital terrain data, target object library, weather predictions, etc.), an **intentions** module which seeks to carry out the **goals** (or mission plan), and implement certain preprogrammed **acts** of the platform and its sensors.
- An **act editor** contains an array of 'primitive' acts that can be assembled to create complete tailored actions according to guidance from the **user interface** (or human robotic interface).
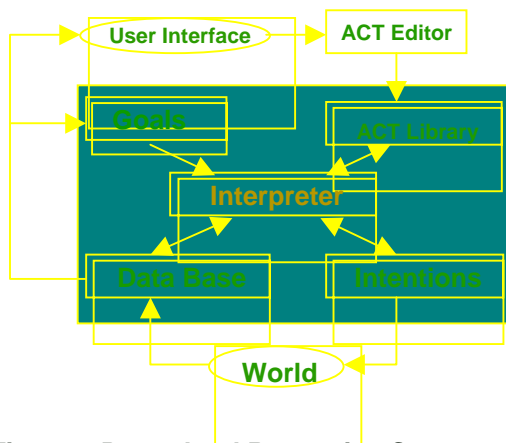
Figure 7 Procedural Reasoning System Architecture

Real-Time Computing System Architecture[8]: developed for ground vehicles by NIST involves a similar cycle of **planning** (red), **acting** ('executors' also in red), **sensing** and **perception** ('sensor/sensor processing' in green) as well as the data maps of terrain, terrain features and icon representations, analysis (cost–risk for different plans and various spatial scales), **analysis** (an early

attempt to use the variable scale world model to make decisions about plans and actions). Figure 8 provides details for study.

Collaborative Autonomy Architecture[9]: The Lockheed Martin Company has developed a general architecture that permits a high degree of IA for individual platforms as well as multiple entity collaboration. One objective of this architecture is to allow a single operator to command multiple vehicles with little more workload than a single vehicle. Although the terminology for this architecture is different, it contains the same three general metrics and the same six IA Mission Complexity elements discussed above.

- **Mission Planning** – develops plans for the team and for individual vehicles
- **Collaboration** – manages team formation and interaction among team members
- **Contingency Management** – detects, assesses, and responds to unexpected events
- **Situational Awareness** – creates Common Relevant Operating Picture (CROP) for team
- **Communications Management** – Manages the interaction with the vehicle's communications systems.
- **Air Vehicle Management** – Manages the air vehicle's flight systems, sensors, and weapons.
- **Resource Meta-Controller** – Manages processing resources and dynamically allocates them to different components as necessary. This element incorporates the key intelligent agents used to draw inferences and make decisions, as well as various functional modules and knowledge/data models.

These components are designed to work in concert to achieve goals without violating mission constraints. This system architecture allows collaboration within the autonomous team as well as other systems external to the team. The approach is *extensible* to permit novel algorithms to be added with a minimum disturbance and it is scalable because collaboration has been incorporated in all key components. The software is directly translatable from simulation to flight vehicle.

[7] SRI International. www.ai.sri.com

[8] *4D/RCS: A Reference Model Architecture for Unmanned Vehicle Systems,* James Albus, et. al., www.isd.mel.nit.gov/projects/res/

[9] *Collaborative Autonomy for Manned / Unmanned Teams*, Steve Jameson and Jerry Franke, American Helicopter Society 61st Annual Forum, Grapevine, TX, June 1-3, 2005.
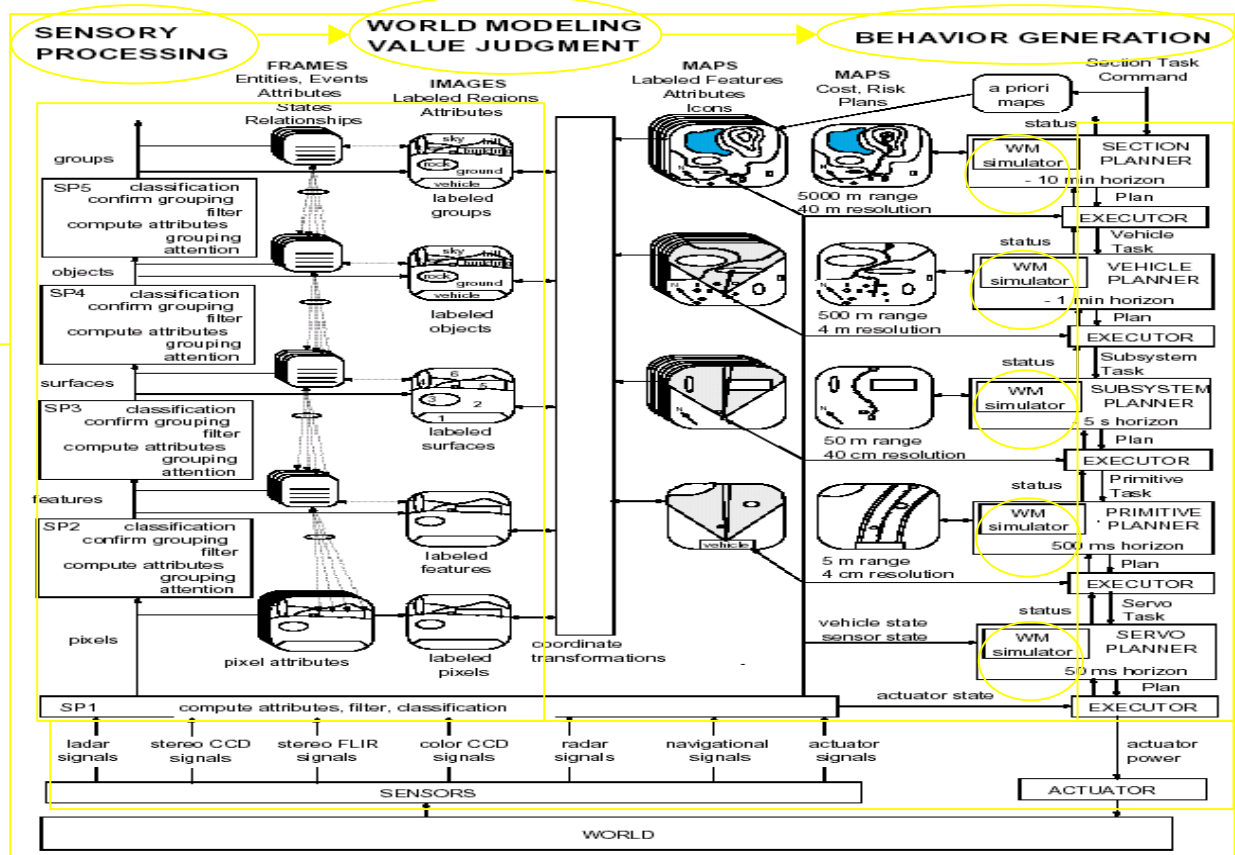
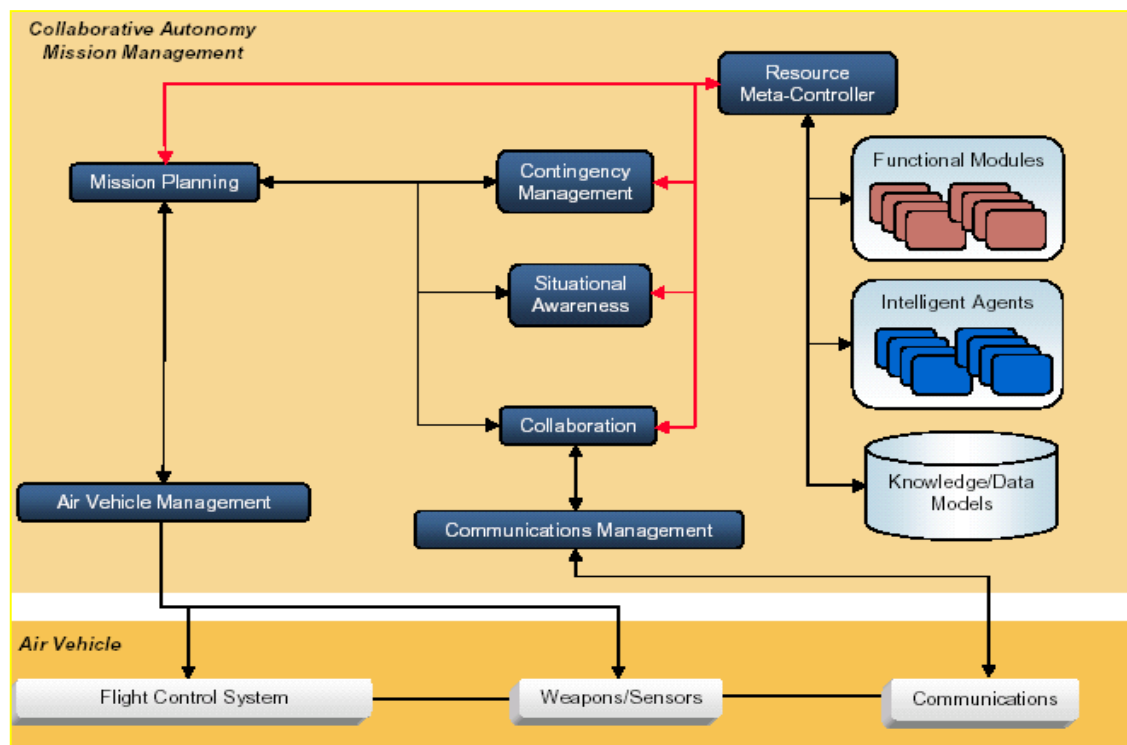*Figure 8 Real-Time Computing System Architecture*

Figure 9 Collaborative Autonomy Architecture

The State of the Art

The remainder of this paper addresses the accomplishments in Intelligent Autonomy in each of the six mission complexity elements. Wherever possible, an example is provided of the reduction to practice, as represented by actual flight demonstrations. The survey is current as of mid-2005.
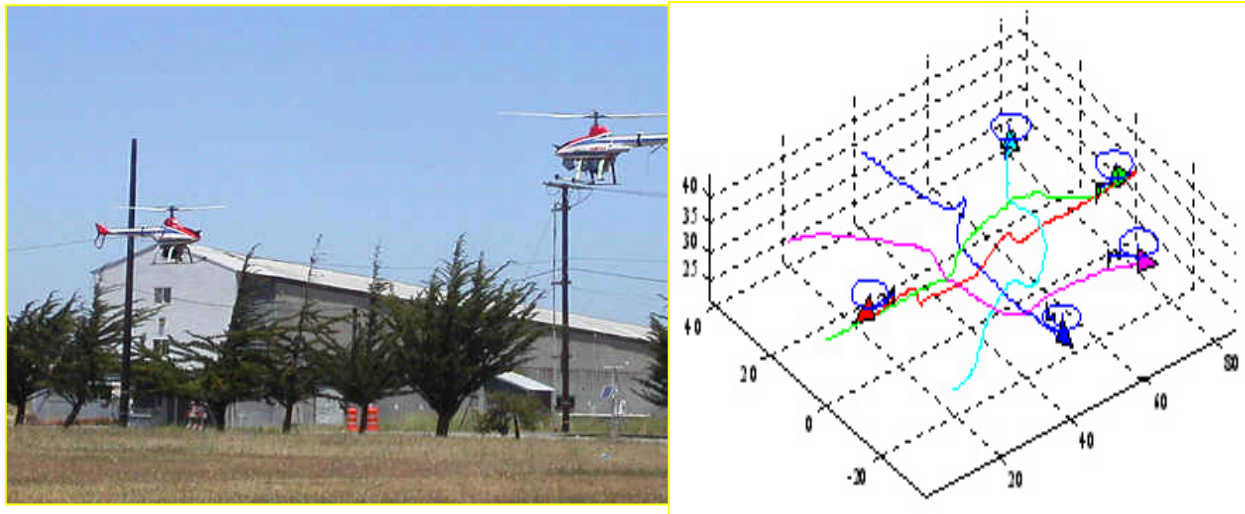
Planning Accomplishments

Flight path planning and dynamic replanning for VTOL UAVs has achieved several significant milestones. An integrated approach for the autonomous landing of VTOL UAVs was developed as part of the US Army's Precision Autonomous Landing Adaptive Control Experiment (PALACE) at NASA Ames Research Center[10]. This approach employs machine vision technologies for the determination of a safe landing point in a non-cooperative environment. It is intended to provide precision vehicle positioning and object avoidance information around a landing zone. GPS is used only for general navigation to the objective area. The flight demonstration was performed on a modified Yamaha RMAX equipped with (2) stereo black and white and a single color video camera. Real-time in-flight computing of the Safe Landing Area Determination was accomplished in under 5 seconds. Landing area objectives included: Landing Site Size (diameter) < 6.25 m; Landing Surface Slope < 15 degrees; Landing Surface Roughness (obstacle height) < 10 cm; Landing Position Accuracy < 1.2 meter.

PALACE Landing Mission
- On-board intelligent decision making
- Obstacles in landing zone

4. Arrival at Landing Zone
- Survey landing zone at 500 feet
- Rapid spiral descent to 100 feet
- Fuzzy logic heading estimation

5. Vision Based Descent and Landing
- Stereo vision elevation mapping
- Safe landing area determination
- Machine vision feature tracking

1. Pre-flight Mission Planning
- Define full PALACE mission
- Specify intermediate GPS way points
- Specify location of landing zone

3. GPS Way Point Navigation
- Terrain / obstacle free altitude

2. Mission Execution and Control
- Monitor mission status and actions
- Operator has decision making ability
- Limited re-tasking of vehicle

Figure 10 Precision Autonomous Landing Adaptive Control Experiment

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[10] *Full Mission Simulation of a Rotorcraft Unmanned Aerial Vehicle for Landing in a Non-Cooperative Environment*, Colin Theodore, Steve Shelden, Dale Rowley, Tim McLain, Weiliang Dai, Marc Takahashi American Helicopter Society 61st Annual Forum, Grapevine, TX, June 1-3, 2005.

A second example of real-time reactive path planning is shown below, wherein complex autonomous collision avoidance of two RMAX helicopters and 3 'virtual' helicopters was demonstrated. The Intelligent Machines and Robotics Laboratory at the University of California performed this work.

Figure 11 Autonomous Collision Avoidance Demonstration

<u>**Act Accomplishments**</u>

During 2005, the final demonstrations of the DARPA Software Enabled Control (SEC) program were completed, representing the culmination of over 7 years of research with contributions from many different organizations. The figure illustrates the multiple elements of the demonstration, which included:

- An open system UAV that enabled a wide array of different software approaches to be tested
- Fault detection and accommodation and fault-tolerant adaptive flight control
- Reconfigurable control
- Envelope protection
- Vision aided inertial navigation and vision-based obstacle avoidance
- First air-launch of a hovering aircraft (ducted fan micro UAV).

Figure 12 DARPA Software Enabled Control (SEC) Program Final Demonstration

Sense Accomplishments

IA equipped UAVs are able to take advantage of the latest generation of lightweight, high resolution, all weather sensors, including:

- Low cost inertial and GPS navigation
- Multi-spectral and hyperspectral imagers
- High resolution EO/IR imagers
- LADAR / LIDAR three dimensional imagers
- High resolution Ku/Ka SAR/GMTI radars
- Foliage penetrating UHF SAR/GMTI radars

Significant airborne demonstrations have included X and Ku band SAR change detection, detection of targets under foliage using a UHF radar, hyperspectral imaging of different materials, LIDAR mapping of urban terrain, LIDAR imaging of obstacles and wires (down to 15 degree obliquity angles). Perhaps the most exciting development (not yet flown however) is the Flash LADAR under development by several organizations. This sensor holds promise for rapid, high-resolution detection of targets under foliage (so called 'peek through' mode) as illustrated below. The figure illustrates a horizontal image taken through foliage (top) and a computer generated image perspective (bottom) that allows the object to be observed.
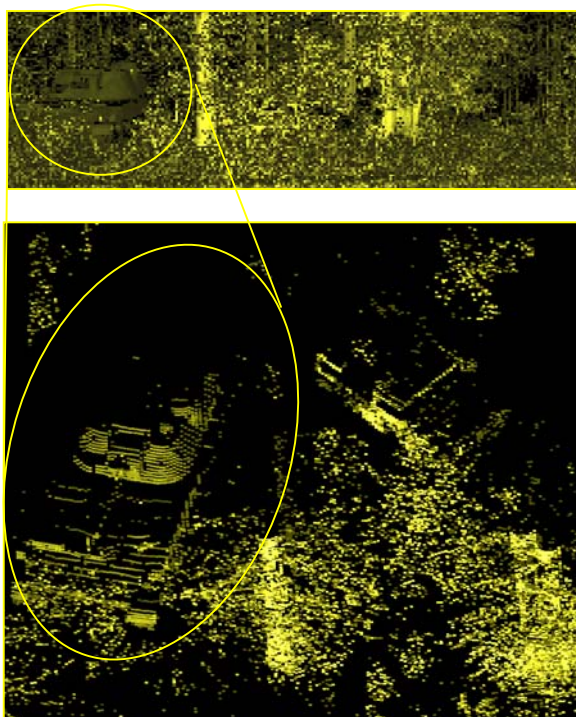
Figure 13 LIDAR Detection of an Object Hidden by Foliage

Perception Accomplishments

Vision and perception research is one of the most active areas of IA, although platform developers have very little insight into this area at present. The research in this area varies from relatively straightforward imagery processing to highly sophisticated attempts to model the human visual system.

Image manipulation and tracking: A demonstration of imagery manipulation is seen in the photo below which illustrates an RMAX at the University of California employing real-time vision processing to track the motions of a simulated ship – in this case the 'ship deck' landing area is the platform shown mounted on the trailer with realistic pitching, rolling, heaving deck motions controlled by a set of actuators. The technique involves analysis of the image for parallax, relative object size, and other techniques to estimate distance, rate and attitude. This data is then coupled into the vehicle flight control and navigation functions to perform the landing operation. Other research by Carnegie Mellon University, Georgia Institute of Technology and the University of Florida have exploited vision methods for tracking of moving objects, navigation in GPS denied environments, and aircraft flight attitude and rate control of micro UAVs.

Figure 14 Vision-based Landing of a VTOL UAV on a Simulated Ship Deck

Image Processing and Feature Extraction: Another significant advance in vision perception is the capability to take streaming video images and

perform various types of perception analyses. Sarnoff Laboratory in the U.S. and OCTEC Corporation in the U.K. have developed systems that are able to perform a number of useful tasks, including:

- Electronic stabilization of imagery, effectively increasing the range and resolution of sensors
- Image matching and change detection
- Detection of motion including "bipeds" (personnel) and other moving objects
- Geolocation, 'tagging', tracking, and counting of moving objects within the field of view
- Creation of three-dimensional views from multiple perspective EO/IR images
- Creation of digital mosaics to form contiguous imagery maps that can be registered and overlaid on other maps and images
- Fusion of IR and EO sensor images to create higher contrast combinations in conditions such as smoke, fog, and shade.

Image Research: Many more perception research activities are on going. For example, in the area of computer vision alone there are over 300 research groups working in a wide diversity of areas. Some of the areas relevant to IA are listed below.

Image Resolution and Quality
Super resolution imaging
Multi-resolution processing
3D Vision
Optic Flow
Image fusion
Image segmentation
Texture segmentation

Motion Detection
Motion segmentation
Structure from motion
Human gait tracking

Object representation and recognition
Edge finding
3D object reconstruction
Tomography
Urban modeling
Pattern analysis
Shape modeling
Reflectance modeling
Occlusion
Statistical Target Recognition
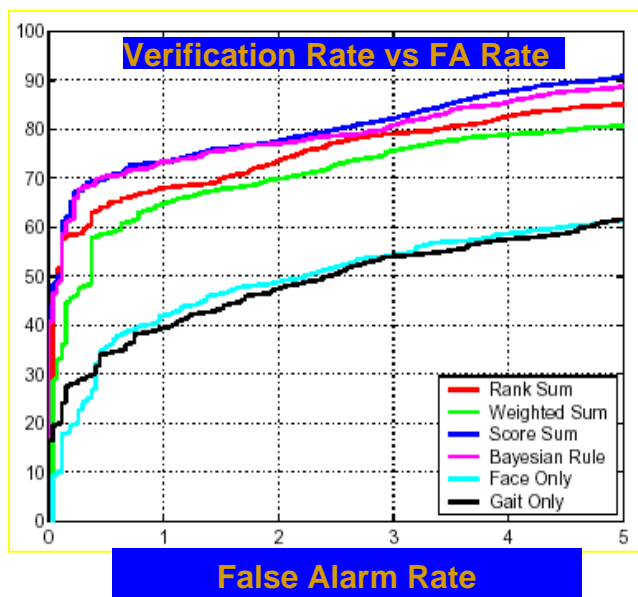
Human Identification
Facial analysis / biometrics
Skin detection

Hand shape identification
Hand gesture recognition
Real-time face tracking
Eye/gaze tracking
Lip reading

Cognitive Perception
Active Perception / Visual attention
Visual learning
Intelligent interfaces
Biological vision

Human Identification at a Distance: One application of some of the computer vision perception research is "Human Identification at a Distance". This DARPA project integrates elements such as gait recognition, gesture recognition, facial recognition, pose (aspect) independence, resolution independence. Some results are shown below.

Figure 15 Metrics for Human Identification at a Distance

Analyze and Decide Accomplishments
Higher-Level Cognitive Functions: Given accurate perception information, the IA system must next perform reasoning and make decisions with varying levels of uncertainty. The perception element builds the inner, robotic interpretation (or model) of the World. The cognitive aspect allows reasoning about the model of the World (including verifying that it is correct by testing it against sensor data). *Analyze and Decide* is therefore the

domain of higher-level cognitive functions that permit reasoning about goals, actions, beliefs, perceptions and other matters. These functions are highly sophisticated when contrasted with the basic planning and acting (or reactive) aspects of IA and the trivial case of GPS navigation.

Contributions from Artificial Intelligence Research: Traditionally the first half-century of Artificial Intelligence is divided into seven areas. Some relevant progress in each area is described below.

- Vision – previously described
- Planning and Problem Solving – partially described previously, but more broadly inclusive of the entire domain of spatial, temporal and knowledge representation.
- Knowledge Representation – includes the modeling aspects of vision research previously described, but extends to other sensor and information domains as well
- Learning – Prior demonstrations have been based upon training of neural networks with vision sensors or servo actuator commands; now extending to goals, actions and beliefs.
- Search – recent demonstrations have included optimal path searches with EO/IR and radar sensors. The general problem is extended to include knowledge domains.
- Natural Language Understanding – recent demonstrations have included a series of spoken commands to a UAV helicopter to generate a series of actions.

Logical Calculus - Based Inference and Reasoning: Situational calculus formalizes the reasoning process by employing a semantic language for inference and reasoning. These methods are symbol-based and require a good model of the environment in order to achieve success. Minker[11] provides a recent survey. Logic approaches have clear semantics with carefully defined properties. A leading example is the Predicate Logic Calculus, a symbolic reasoning system based upon formal logical procedures. A promising aspect is the ability to exercise a degree of 'free will' to perform actions or withhold other actions (within narrow domains). One major challenge of logical approaches is called 'the frame problem', wherein a large number of axioms are needed to represent changes in the situational calculus when reasoning about actions. In other words, an exponentially increasing number of

possibilities hold for the succeeding states, based upon actions taken in the current state. This aspect may limit the capability to deal with complexity. A second challenge is that first-order logical methods represent truth and direct consequences (monotonic logic) and therefore does not continuously reevaluates decisions based on new perception information. If an inconsistency enters the knowledge base these methods may fail. These factors lead to a requirement to fully understand the domain that the robot operates within in order to avoid an exponential growth in software and computing. Recent advances have included a functional representation of actions (Strips language) that avoids the frame problem. Other research includes sensing, improving perception, complex planning, interleaving planning and acting, non-monotonic reasoning, abductive and inductive reasoning, modeling beliefs and machine learning.

Applications of the logic-based approach to cognitive robotics include the SRI Procedural Reasoning System, depicted in figure 7. This system has been applied in limited domains (ground robots moving through buildings) with some success, and has been used to simulate more complex aerospace applications.

Process Algebra - Based Inference and Reasoning[12]: Process algebras use symbolic logic and logical operations to permit manipulation and mathematical solutions within the framework of axiomatic theories that incorporate an algebra for manipulating and coordinating processes. Some advantages include the modeling of sub processes as 'atomic steps', which can then be pieced together, and non-deterministic and concurrent processes can then be modeled and optimized, because the factors affecting the process are modeled mathematically. Complex actions are described by functions of the atomic steps combined by a small set of basic algebraic operators (e.g., $a*(b+c)=a*b+a*c$). Logical processes combine and integrate these steps by enabling functions such as combination, merge, deadlock, and communication.

IA Algorithms: A number of probabilistic learning, reasoning and decision processes are currently being used for limited domain problems. Examples include:

[11] *Logic-Based Artificial Intelligence*, Edited by Jack Minker, Kluwer Academic, 2000

[12] *Applications of Process Algebra*, Edited by J.C. Baeten, Cambridge University Press, 1990

- Markov Machine Learning
- Partially Observed Markov Decision Processes
- Bayesian Classifier Networks
- Expectation-Maximization Methods
- Neural Networks
- Graph Theoretic Methods
- Fuzzy Logic
- Genetic Algorithms

The architectures shown in figures 8 and 9 and the planning and acting examples of figures 10, 11 and 12 utilize some of these mathematical methods.

For the VTOL UAV applications a key additional requirement is to operate in near real-time, so that 'pruning' and 'parsing' techniques must be invoked to prevent combinatorial explosion.

In the future, recent discoveries in biological vision processing and the rapidly advancing field of cognition research may result in the emergence of new computational theories of intelligence.

The Rate of Growth of Cognitive Systems
The optimistic prospects for rapid growth in Intelligent Autonomy for VTOL UAV's are based upon the synergism of two key trends:

Growth of Global Robotics Market
The first trend is the rapidly expanding global market for robotics and intelligent systems. Consider these indicators:
- UN World Robotics Survey (2003) – industrial robotics is a $5.6 B per year industry, growing by 7% a year. However, the greatest short-term growth will be in the domestic area.
- Business Communications Company   (April 2003) – estimates total artificial intelligence system sales to grow from $12B in 2002 to $21B in 2007 at a rate of 12.2% per year.
- Australian IT (April 2002) – enterprise automation, which includes autonomous software agents, will be worth $250B by 2010.
- The Korea Herald (10 November 2003) – The global embedded software market is expected to reach $138.4 B in 2007, registering an average 9.25% average annual growth.
- The Economist Technology Quarterly (June 2004) – sales of business intelligence software, will grow by 8.5% a year.
- The Los Angeles Times (6 June 2004) – computer game sales reached $11.4 B in 2003, (AI is a component of many games).

The Exponential Growth of Technology
These advances in robotics are being matched by a second trend – the continued exponential growth in computer speeds. The analysis by Kurzweil[13] shown below demonstrated that powerful market forces are driving these technological trends.
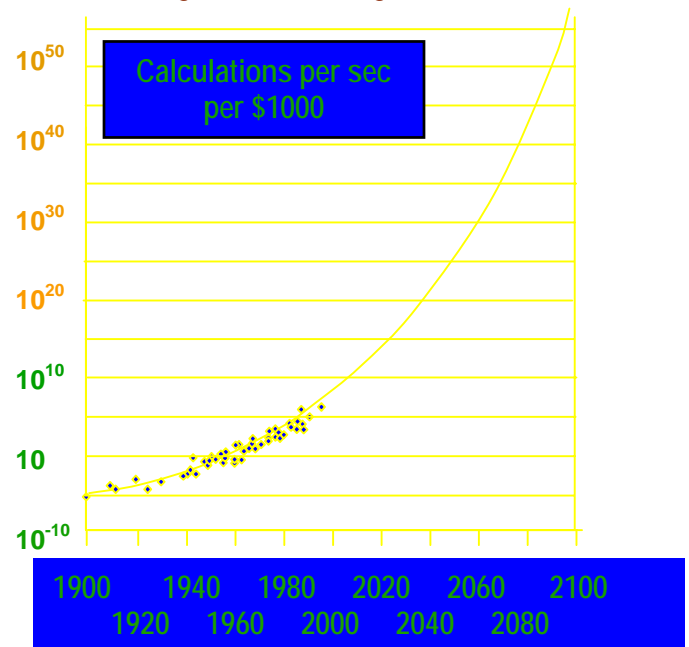
Figure 16 Exponential Growth in Computing Power Will Drive Intelligent Autonomy

In other analyses Kurzweil demonstrated that the exponential phenomenon applies to other areas of technology that are applicable to IA, such as networks, sensors and micro mechanical devices.

Conclusion
This survey has demonstrated that we are rapidly entering the *Age of Intelligent Autonomy*. The synergistic impact of economical and technological forces is creating an exponential rate of growth – almost entirely outside the field of rotorcraft. If higher-level cognitive algorithms can match the other IA technology rates of growth, then the range of applications will expand dramatically. For VTOL UAVs, IA can enable unprecedented situational awareness and will ultimately change the current operational paradigm from 'time-sensitive targeting' to '*Monitoring the Time Evolution of the Battlespace'*, thereby providing the operator with the capability to perceive situations in detail and to select the optimum time and location of action.

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[13] *The Age of Spiritual Machines*, Ray Kurzweil, Penguin Books, 2004