Artificial Intelligence Grounded in Reality

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ABSTRACT
At the Machine Intelligence Laboratory (MIL) in the Department of Electrical and Computer Engineering at the University of Florida (UF), we seek to develop fundamental knowledge and gain practical experience in the design, realization, and application of intelligent, autonomous, sensor-driven, behavior-based robotic agents. These agents generate knowledge, share information and learn to improve their performance with experience. We seek to combine a wide variety of advanced technologies to give computer-driven autonomous machines the ability to learn, adapt, make decisions, and display behaviors not explicitly programmed into their original capabilities. We use the term agent and robot interchangeably.

Autonomous refers to the independent control of each agent/robot by its embedded computer. (The term 'robot' comes from a Czechoslovakian word meaning "forced servant," and was first coined in the play Rossum's Universal Robots by the writer Karel Capek in 1920). The term 'mobile' refers to the ability of the robots to maneuver around an environment un-tethered and self-reliant. In this context we define machine intelligence as the ability to build machines that exhibit a high degree of sophistication and can operate autonomously in 'their' environment. For example, a roach is a highly intelligent insect (as evidenced by the US$100 million industry designed to attempt to control them, especially in Florida), and thus, a 'roach-like' machine would also be considered 'intelligent.' At MIL, we define artificial/machine intelligence is simply "computer intelligence grounded in reality," which answers the question 'what intelligence can be realized?'

Keywords
Robot, machine intelligence artificial intelligence, autonomous.

1. THE MILIEU
If you walked into the MIL on a typical day, you might be surprised to find 10-20 college students from a variety of engineering and science disciplines, sitting wherever they can and surrounded by robots in various stages of completion. Building a robot requires that the designer

- integrate control, electronic, and mechanical systems into a working device,
- confronts the interactions between different subsystems,
- has the opportunity to trade off between the different subsystems in constructing their robot.

The dilemma of building an autonomous robot engages the robot designers in the issues of real-world problem solving; multidisciplinary teamwork; and creative, critical thinking. Building an actual robot, rather than programming a simulation, forces that roboticist to immediately confront the non-ideal nature of real-world devices, and provides immediate feedback about the success or failure of their ideas. By requiring everyone to work on a team, the lab encourages students to pool their individual expertise, allows them to specialize on specific subtasks, and gives them experience in developing the interpersonal skills to articulate and defend their views and ultimately reach a consensus that is best for the group as a whole. Because the lab attracts participants from a variety of disciplines, students learn that very different perspectives can be helpful for solving a hard problem; they are motivated to learn each other's language to break down disciplinary barriers. There are three ways in which students are encouraged to take ownership of their education in this context, and to think critically: first, the excitement of building a working device; second, the desire to do well under public scrutiny; and third, the recognition that there is no single correct solution, which encourages creativity.

2. ROBOTIC (AD)VENTURES
Historically, our efforts have been focused on developing ground, air and underwater autonomous agents designed to accomplish specific tasks. For the purposes of this article, we will describe four such projects currently under development (these are second- to sixth-generation designs). These were selected to give a flavor for the challenges in each of the major areas of design and to illustrate some of the design philosophies and constraints guiding the development of each agent.

2.1 SubjuGator
SubjuGator (**Figure 1**) (www.mil.ufl.edu/subjugator) is an autonomous underwater vehicle designed and built by students of the MIL to compete in the annual Association for Unmanned Vehicles Systems International (AUVSI) (www.auvsi.org) underwater competition. SubjuGator has placed in the top three on five separate occasions in the AUVSI underwater competitions since the competitions began in 1998. An entirely new SubjuGator was constructed for the Eighth Annual AUVSI Underwater Competition, 3-7 August 2005, and it won first place [1]. (A paper on this submarine will be presented at this conference.)

The goal of the competition is to advance the state-of-the-art in underwater vehicles (AUVs) by challenging a new generation of engineers to perform realistic missions in remote underwater environments. The mission requirements change from year to year. To successfully complete the 2005 competition objectives, submarines needed to complete several tasks: pass under a validation gate, mate with a docking station, inspect a pipeline to find a break in the pipeline, drop two markers on the break, locate the acoustic pinger at the center of the recovery zone, and surface in this zone.

Figure 1 MIL'S 2005 SUBJUGATOR SUBMARINE

2.2 Koolio

Koolio (**Figure 2**) is an autonomous traveling refrigerator robot—picture a cross between R2D2 and a vending machine. (R2D2 was an intelligent robot from the movie series *Star Wars*.) It is designed for use on the 3rd floor of the MAE-B building at UF. The MIL, classrooms and the MIL professor's offices are all on this floor. Since professors are always working diligently in their office and sometimes can't even find the time to get up and get a drink, Koolio delivers drinks and food to the wary and irritable professors (and students).

Figure 2 MIL's Koolio Robot

To accomplish this task, the potential user logs on to the network and tells Koolio that he would like, for example, a Diet Coke. Koolio receives this signal through its wireless card and determines the room number that originated the request. It leaves its docking station at the MIL lab and proceeds to the hallway. It navigates the hallway with a variety of sensory inputs (including sonar for accurate long distance coverage and obstacle avoidance, infrared (IR) for close-range obstacle avoidance, shaft encoders for accurate navigation once location is determined, and cameras for reading room numbers on the wall adjacent to the offices. Koolio locates the user's office and delivers his Diet Coke (retrieved via color analysis using a camera mounted on its arm, thus averting impending disaster [2]). After recording the debt, Koolio leaves the room and returns to its docking station to recharge and wait for the next call.

2.3 Gnuman

Figure 3 Omnibot 2000

In the summer of 1999, a humanoid robot, Omnibot 2000 (**Figure 3**), was developed at MIL to ultimately conduct lab tours and presentations for visitors [3]. Omnibot was designed to be a personal assistant, capable of helping the elderly or disabled, and to entertain and perform. Commands were issued orally to Omnibot, and it would respond by repeating the words and performing the specified behavior. While in its "obeying commands" behavior, the user could instruct it to move its arms, grippers, head, and body. Omnibot was a pseudo-slave, performing any task the user requested. His claim to fame was singing and dancing to The Village People's "YMCA".

Since Omnibot could manipulate a mouse, in the following year, Scott Nortman and Eric Schwartz had Omnibot run a 15-minute PowerPoint introductory presentation on the first day of the *Digital Logic and Computer Systems* course while the professor (Eric Schwartz) hid amongst the students. The robot introduced itself as Robo-Schwartz, the teacher for this course during the semester. At the end of the presentation the robot stated, "I can not continue with this deception. Here's Dr. Schwartz!" At this point, Eric came left his seat and made his way to the front and said, "and this is what you will be able to build upon completing this course and a few others!" The students were delighted and burst out in enthusiastic applause. Unfortunately, Omnibot (made of plastic and wood) was not designed for long-term use; it broke apart one semester later on the way to a presentation when the truck transporting it went over a deep pothole. The Gnuman (sounds like "new man") project (**Figure 4**) was started to advance humanoid research and create a robotics lab/class tour guide to replace Omnibot. Gnuman goals include artificial cognition, natural language processing, active stereo vision, path planning, autonomous navigation, inverse kinematics, manipulator control, and human-humanoid interaction [4].

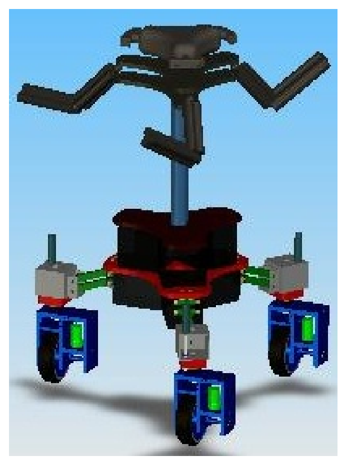

Figure 4 MIL's Gnuman Robot

2.4 Micro-Air Vehicles (MAVS)

Micro Air Vehicles (MAVs) (**Figure 5**) are tiny (18" to 4" wing span) self-propelled aircraft built from innovative materials. UF (under the direction of Peter Ifju) is a world leader in MAV design. The UF team has been competing in the International MAV Competition since its inception in 1997. UF teams won each of the past 7 years, including the 9th International Micro Air Vehicle Competition at Seoul, South Korea's Konkuk University [5]. UF will again compete in the 10^{th} International MAV Competition at Brigham Young University, Provo, from May 19^{th}-20^{th}.

Figure 5 Micro Air Vehicle

MIL goals are to develop basic research and technologies, enabling unprecedented capabilities for MAVs and small Unmanned Air Vehicles (UAVs). Potential MAV missions (**Figure 6**) are search and rescue, moving-target tracking, immediate bomb damage assessment, and identification and localization of interesting ground structures. The aim is to allow such missions within very adverse environments, such as complex urban terrains, without substantial prior knowledge about these settings [6].

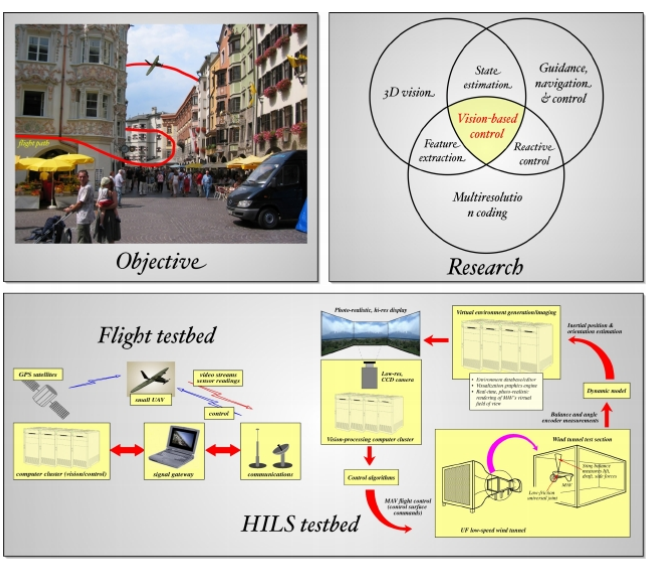

Figure 6 Micro Air Vehicle Mission

3. SPECIAL CHALLENGES

Autonomous agent designs require a number of technologies and disciplines to blend together to arrive at a suitable realization. An agent consists of five basic subsystems:

- a physical platform (whose design criteria depends on whether the agent is an air, water or ground vehicle and if ground, whether designed for indoor or outdoor use)
- actuation mechanisms (linear and non-linear actuators, motors, servos, wheels, and gears)
- embedded computer(s) [*micro*controllers, DSP computers, general-purpose computer boards, disk drives, and many application-dependent computer peripherals]
- a power system (battery technology, charging systems, power isolation)
- various sensor modalities (light, heat, motion, force, electric, electrostatic, magnetic, ultra-sonic, mechanical, gyroscopic, temperature, pressure, depth, GPS, and other sensors)
- behavior, control and intelligence software (operating system, device driver, application, communication, protocol, master/slave, parallel and serial, and low-level programs written in languages ranging from assembler and BASIC to C/C++ and Java).

For MAVs, weight and power consumption are deal breakers. For underwater vehicles, ultra-sound and water tight connectors and cabling are essential. For ground vehicles weight and terrain and whether the vehicle is intended for indoor or outdoor use determines sensor modalities. For agents that interact with humans, voice, vision, and safety are the critical issues. All unmanned vehicles need to have kill switches and fail safe mechanisms to avoid self-destruction and harm to people and the robot environment, especially during testing. Furthermore, every design needs to use less power and cost less than its predecessor.

In addition, as autonomous agents are developed and constructed, the designer must follow strict and acceptable design methodologies, incorporating modular construction and providing for the testing of each module. As the modules are verified, integrated subsystems of module groups must subsequently be tested. Designs must incorporate feedback to the user, both for aid in debugging and so the designer can understand the actions and motivations of the robot. Once an autonomous agent is deployed, it "does its thing" regardless of the current wishes of its human operator. Autonomous robots have "a mind of their own;" there must be a way for the agent to communicate to the user its inputs and decisions for future evaluation and reprogramming. Autonomous agents are non-linear, time-varying, non-ergodic, high-order, simultaneous and non-trivial systems. Not exactly what our colleges teach in our engineering curriculum. These constraints are both frustrating and sources of great motivation for the would-be robot builder, requiring innovation for novel ways to measure, quantize, and gauge performance.

Robots must also improve and adapt with use. Agents that do not improve performance are doomed to sit on the shelf. For example, once Koolio figures out a path from MIL to my office on the third floor of MAE-B at UF, it should navigate in an optimum way and negotiate the hallways so as to act with intelligence. (On the first day it might be sufficient for the robot to bump all the walls and try all the rooms between MIL and my office; but a week later, we all expect the robot to quit acting blind and get there as fast as possible.) Machine Intelligence demands that these types of robots perform machine learning to improve performance in contexts yet to be studied in the artificial intelligence (AI) field. We are all victims of our own success in the PC field, having trained the general population to expect bigger, better, cheaper, sleeker, and faster, with more sophistication and intelligence in every passing year. Robotics and machine intelligence have to live up to such expectations if they are to get out of the laboratory and into the consumer arena.

4. CURRENT SYSTEMS

There are typically no off-the-shelf components available for the a robot designer's ultimate goal. While one can find some subsystems (e.g., GPS modules) for ground vehicles, there are often few equivalent subsystems for air or underwater agents. While a ground vehicle might be able to carry several 10 kg (25lb) 12-V motorcycle batteries, an MAV may only have a 15-25 gram payload. Autonomous agent designers have to develop an innovator's mindset: "If I can't buy it, I can build it." Nowhere is this more evident than in the embedded processor boards, platform mechanisms, and sensor modules of our agents.

4.1 Embedded Processor Boards

Every robot needs some sort of embedded computer to accomplish its design goals. We typically need a medium speed 8-bit, state-of-the-art microcontroller with features including many I/O pins, analog-to-digital (A/D) ports, Serial and Parallel I/O, inter-integrated circuit (I^2C) bus, general-purpose timers, pulse-width modulated (PWM) pins, flash, static RAM and EEPROM, power regulation, and software support. While there are many vendors supplying general-purpose circuit boards, we have found that we generally have to design our own microcontroller boards in order to meet weight, power, current, heat, and packaging constraints. Microcontroller boards are reasonably designed using general-purpose design tools such as Protel, EagleCad and professional tools such as Cadence. We routinely design embedded boards based on Atmel, Motorola, Intel and PIC processors. In the case of Atmel, for example, there is a large Internet-based community with extensive user and support groups. Almost every robot we have built in the last few years has had at least one Atmel-based embedded board to control all of the agent's low-level functions.

For applications requiring more computation, Intel Pentium-based boards and AMD boards capable of running Linux or Windows XP (or Windows embedded OS's including embedded XP, Windows CE and Windows Mobile) are available off-the-shelf, albeit, at a price. SubjuGator, Koolio and Gnuman have multiple embedded *microcontroller* and Pentium computer boards while our MAVs use tiny MIL-developed custom *microcontroller* boards. To do certain tasks, such as using hydrophones to sense multi-frequency pinger locations underwater, DSP boards may be required to perform fast Fourier transforms (FFTs) and other digital filtering techniques. In our lab, SubjuGator 3 had an embedded DSP board, and SubjuGator 5 used an FPGA to accomplish the required digital signal processing.

Most robot systems, depending on weight and torque requirements, require such things as optical isolators to isolate electrical the noise of power systems, motor drivers and servo controllers from CPUs and other noise sensitive circuitry (e.g., voice synthesis and recognition ICs and small signal sensors). We have found that nearly every sensor module requires its own interface board in order to function properly for long periods of time. In addition, underwater vehicles require specially made waterproof connectors and cabling that is able to withstand the pressures that are dependent on the depth requirements.

4.2 Platform Construction

Robotic platforms are built from metal, plastics, wood, and composite materials. For small platform design we have found that multi-ply, aviation grade balsa wood provides a reasonable and affordable approach to build solid and durable multi-purpose agents. We especially like the use of wood to build prototypes. Most body parts in MIL are designed using AutoCAD, rendered in three dimensions, and then cut using a file generated from the design software program. Whether wood or plastic, or for laser or conventional cutting, a file generated by AutoCAD (or similar packages) is the standard. For larger ground and underwater vehicles, regular CNC machining of metal and other parts is essential. Special gearing for motors and bearings may also be required, as well as innovative steering and braking mechanisms. Most ground vehicles will require special power busses and racks to mount vibration resistant components such as hard disk drives, computer peripherals and vision systems.

4.3 Sensor Modules

A robot's interaction with its environment is essential to its autonomy and adaptability. Sensors provide the basis for all behavior programming and intelligence. A machine that cannot sense an event cannot react. Great advances have been made in sensor modalities and technology. While better and better sensor packages are available off the shelf, we find that we often have to design our own sensor modules including the necessary electronic interface boards. The predominant design criterion is to get multiple inputs, either different type sensors or modalities or views of an event, to react intelligently and properly to the situation. Sensor and event sensing redundancy is essential. Often, behaviors are arranged in a subsumption or priority-based architecture via arbitration and the triggering of arbitrator events is tied intimately to this redundancy [7].

For example, if your robot uses IR or sonar to detect an obstacle, and the obstacle is in the sensor's dead zone, a bump switch can trigger a back-up-after-bumping-the-obstacle behavior in reaction to the blind spot. This is a kind of last resort behavior: "if I do not see the obstacle ahead with my regular sensors, and I get a bump indicating I am hitting an obstacle, then I should back up and turn to avoid multiple encounters with the obstacle. Otherwise I'll assume no obstacle and move ahead as if no obstacle was present."

4.4 Controllers

Non-standard controllers, not just proportional-integral-derivative (PID) controllers, are often required in successful robotic systems. These nonstandard controllers are implemented in software, as opposed to hardware, and here is where the use of Machine Intelligence is demonstrated. Much research has been done in various forms of control, architecture, and learning. The degree of intelligent behavior is often tied directly to the success of the control mechanism and software. Most work published in AI and Robotics journals deal with this aspect of robotics. The advent of low-cost vision systems, such as the $99 CMU cam, X-cams and Web cams, is beginning to change controller design. In our experience, vision systems require other sensor modalities to function properly and should be used primarily as secondary inputs to controllers until the science matures.

4.5 Testing Environment

The creation of a test bed and development environment to test an autonomous agent poses particular challenges and problems to a robot designer. For example, in our autonomous helicopter project, we could hardly afford for the vehicle to crash fro a software malfunction. Thus, we had to develop a special-purpose aerial vehicle research and testing environment designed specifically for the helicopter [8].

Submarines have to be tested underwater and at the same time be able to be retrieved in case of malfunction. Obtaining the UF's Olympic-size pool to test was essential, yet we could not modify or in any way alter the pool environment, which necessitated the construction of portable obstacles and gear to measure performance.

MAVs also pose particular problems in testing and instrumentation. In most cases, we have to use telemetry to send sensor data to off-agent stations and rely purely on data that can be transmitted reliably to test the vehicle while flying. MAVs, while small, can easily get out of range of monitoring equipment, requiring contingency plans for retrieval of the agent during testing. Large autonomous robots, such as Koolio, also pose a challenge when designing testing environments—they can hurt people. Often autonomous agents have to have a tethered mode when they are teleoperated in the presence of humans and only allowed occasional autonomous operation until fully tested and debugged.

4.6 Instrumentation

Our machine intelligence and robotics labs do more development than testing. We build prototypes more than we deploy end-user systems. Furthermore, in a university setting, every student/researcher wants to build anew (everyone feels that they know more and are more savvy than their predecessors). On any given robot, the aim is to sense a full range of environmental stimuli in order to develop suitable behaviors, a practical impossibility. Accuracy is often sacrificed for reproducibility and cost. Reliability is most desirable in robotics applications, but more often than not, the cheaper sensors, when coupled with multiple modalities, can do an adequate job for what can only be considered a straw man design. For example, all mobile robots must perform some sort of obstacle avoidance. Ultrasonics are often used to detect obstacles at distances from 0.5 to 5 m, IR to detect obstacles 3-500 cm and bump sensors are used to accurately detect collisions or contour an unknown obstacle. This is an example of what we call the multiple sensory views of an event required for acceptable agent behavior.

There is an increasing demand in our technology for quantizing anything that can be sensed. Examples include pressure, temperature, distance, tilt, position, bearing, lift, depth, altitude, force, bend, chemical detection, vision, color, texture, frequency, vibration, light (at all frequencies), magnetic force, electromagnetic energy, voice, spectrum, rotation, velocity, acceleration, weight, electrostatic energy, intonation, music, sound, odor, and signal detection, to name a few. If we are to create machines that relate in a more humanly way to the general society, there are probably many more things/events that are desirable to be sensed and reacted to intelligently (in fact, a whole class of machines have been designated as stimulus-response agents, referring primarily to robots that simply react to immediate stimuli in their environments) [9]. Machine intelligence in robotics is best characterized as being in its infancy and as such is more driven by variety rather than maturity. As most robot builders put it, "I just cannot find what I need in anyone's shelf—I must therefore build it from scratch or adapt an existing system." We should also mention the very real possibility of taking something intended for one function and adapting (hacking) it for a completely different purpose than the one intended. Our machine intelligence and robotics labs need nearly every instrument found in the electrical, mechanical, computer, physics, biology, and chemistry labs around the campus—a mega lab if you will (a highly unlikely and unfeasible event).

4.7 Current Developments and Research

Besides SubjuGator, Koolio, Gnuman and the MAV work, MIL is looking into several other robotic projects. These include a ground vehicle (the MILcart) that may be used to pick up a passenger in one location and deliver them to another building. MILcart is also expected to patrol the parking lot adjacent to our building on campus looking for an empty parking space to hold in reserve for MIL staff. We are developing a lawn maintenance vehicle (the MIL Lawn Wizard) that not only cuts grass but also maintains a lawn (by adding fertilizer, weed killer, bug control, and trimming around flower beds). We have also developed a platform based on the NASA Mars Sojourner, which has been used in the annual AUVSI ground vehicle competition. Our helicopter project attempts to realize fully autonomous navigation for reconnaissance missions. On another front, we have developed robotic swarms, which could be used in manufacturing work cell applications and to study robot group behaviors (flocking, cooperation, dispersing, encircling, and attacking). We have recently developed MILee, a 3-in radius fully autonomous robot for our future swarms based on new state-of-the-art embedded computer and microcontroller technology. We have also developed four-, six-, and eight legged walkers to study locomotion (gaits) and develop insect-based platforms for biologically inspired applications and study.

In the area of algorithms we have been using Reinforcement Learning, e.g., Q-Learning and H-Learning, techniques to improve performance and gain adaptability. For example, should Koolio be taken to another similar environment, such as a different building on campus, reinforcement learning could presumably require a comparatively minimal number of repetitions to perform its purpose at a reasonable level of efficiency as compared to direct (human) reprogramming. Q-Learning has been used to obtain better obstacle avoidance and wall-following behavior than those programmed by senior MIL staff [10]. In the area of human-machine interaction, we have been developing an MIL speech/voice device capable of understanding a subset of natural language (English) and generating complete utterances [11]. We are also developing prolog-based algorithms in Linux-based embedded computer boards to attempt to communicate and interact with humans (e.g., in the Gnuman project) with a more natural human-like interface (attempting to convey some sort of robot emotion and feeling).

4.8 Conclusions

From the beginning at MIL, we have identified four philosophical goals for artificial/machine intelligence grounded in reality to flourish in constructing autonomous agents: integration, real-world issues, interdisciplinary teamwork, and critical thinking. Building a robot requires that the designer integrates control in electronic and mechanical systems and produces a working device; confronts the user with interactions between different subsystems; and gives the designer the opportunity to make trade offs between the different subsystems. Our environment also encourages biomedical engineers to confront the issues involved in getting a physical agent to operate reliably in a realistic environment by giving them the opportunity to build their own animal, providing a unique perspective on the many problems that nervous systems actually solve.

In addition to these broad educational goals, this approach to artificial/machine intelligence also exposes students to exciting new research approaches in robotics, instrumentation and measurement and neurobiology. These range from biologically inspired approaches in robotics to computational and physical models of the neural basis of behavior in animals. Thus, the laboratory attracts bright undergraduate students to pursue graduate study in these areas of research. Indeed, some of the same challenges and solutions experienced in our laboratory are surfacing in robotics and neurobiology research around the country.

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