Undergraduate Capstone Projects on Multi-Robot Systems
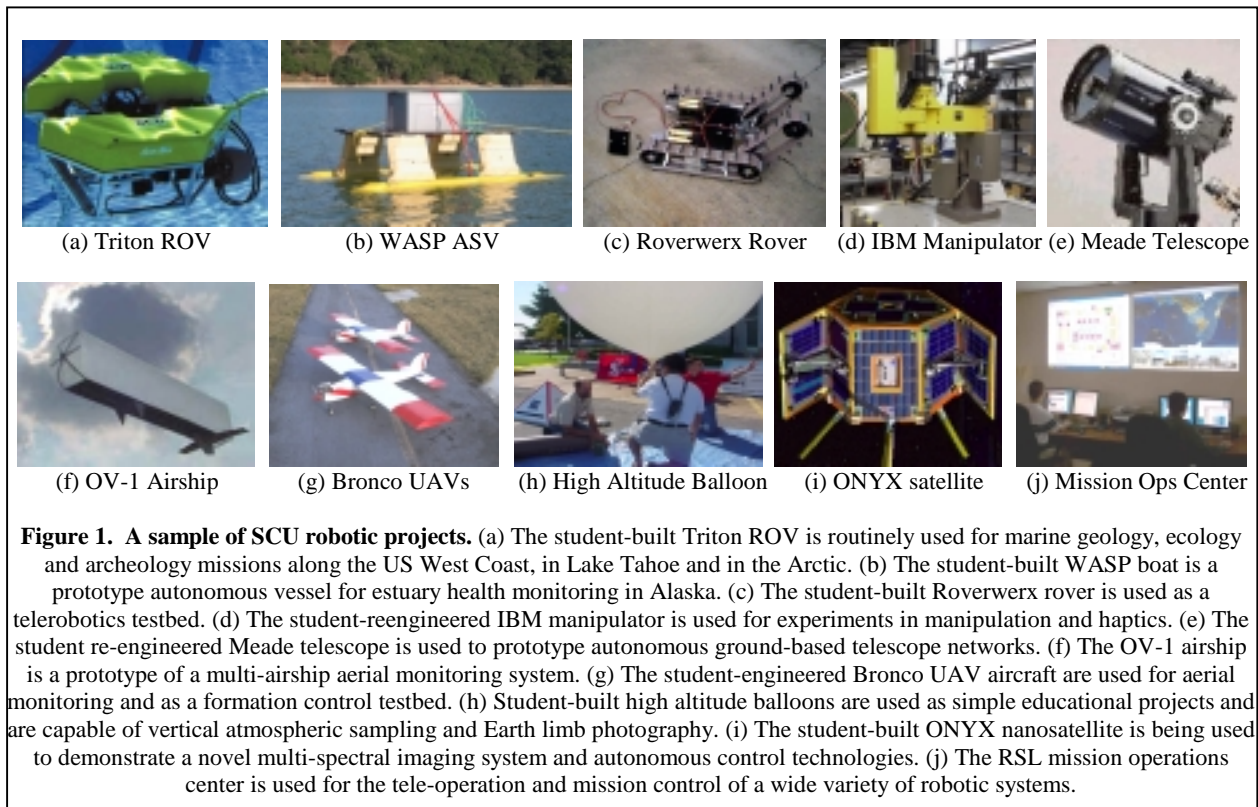
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Abstract – Santa Clara University's Robotic Systems Laboratory has developed a highly successful robotics-based undergraduate education program that provides a wide range of learning experience relating to computer science and engineering fundamentals. A key element of this program is the senior capstone experience, a yearlong project that is typically hands-on, interdisciplinary, and team-based. These projects provide a comprehensive educational environment by exposing students to the breadth of engineering, all phases of a development cycle, and the challenges of managing a group enterprise. Over the past four years, a number of these projects have made significant contributions to the Lab's research program in multi-robot systems, ranging from the development of key testbeds to the execution of significant experimental demonstrations. This article reviews the Santa Clara program, presents specific undergraduate contributions to our multi-robot research program made by senior capstone students, and details some lessons learned regarding the value of such robotics-oriented work in an undergraduate educational environment.

1. The Santa Clara University Robotics Program

Santa Clara University's (SCU's) Robotic Systems Laboratory (RSL) conducts a low-cost, aggressive, integrative educational program focused on the development intelligent robotic systems [1-2]. The centerpiece of this program is a set of yearly undergraduate design projects in which teams of senior students completely design, fabricate, test, operate, and manage high-quality robotic systems. These systems include both autonomous and tele-operated robots that operate in land, sea, air and space, to include underwater vehicles, autonomous boats, terrestrial rovers, industrial robots, airships/aircraft, and spacecraft. Figure 1 shows several of the robotic systems that have been developed over the past five years.

| (a) Triton ROV | (b) WASP ASV | (c) Roverwerx Rover | (d) IBM Manipulator | (e) Meade Telescope |

| (f) OV-1 Airship | (g) Bronco UAVs | (h) High Altitude Balloon | (i) ONYX satellite | (j) Mission Ops Center |

Figure 1. A sample of SCU robotic projects. (a) The student-built Triton ROV is routinely used for marine geology, ecology and archeology missions along the US West Coast, in Lake Tahoe and in the Arctic. (b) The student-built WASP boat is a prototype autonomous vessel for estuary health monitoring in Alaska. (c) The student-built Roverwerx rover is used as a telerobotics testbed. (d) The student-reengineered IBM manipulator is used for experiments in manipulation and haptics. (e) The student re-engineered Meade telescope is used to prototype autonomous ground-based telescope networks. (f) The OV-1 airship is a prototype of a multi-airship aerial monitoring system. (g) The student-engineered Bronco UAV aircraft are used for aerial monitoring and as a formation control testbed. (h) Student-built high altitude balloons are used as simple educational projects and are capable of vertical atmospheric sampling and Earth limb photography. (i) The student-built ONYX nanosatellite is being used to demonstrate a novel multi-spectral imaging system and autonomous control technologies. (j) The RSL mission operations center is used for the tele-operation and mission control of a wide variety of robotic systems.

Once operational, these robotic systems are used by undergraduates, graduate students, and professional researchers to perform compelling science missions and to demonstrate advanced technology. Specific missions have included studies relating to marine archeology, coastal ecological studies, space-based photography, space environment characterization, satellite formation flying and constellation control, and autonomous operations. Collaborators and sponsors for these missions include a variety of government agencies (NSF, NOAA, NASA, DARPA, the U.S. Air Force, etc.), corporations (the Lockheed Martin Corporation, Globalstar, Highships LLC, etc.), academic institutions (Stanford University, the Massachusetts Institute of Technology, the University of Texas at Austin, etc.), and non-profit entities (the Monterey Bay Aquarium Research Institute, the California Space Grant Consortium, the Global Space League, etc.). During the past six years, the development and use of the Lab's robotic systems to support the requirements of these collaborators has resulted in more than $3 million of external funding; this financial support plays a crucial role in providing comprehensive educational resources, addressing extensive logistics needs, and achieving the level of engineering robustness required for a program that includes significant field operations.
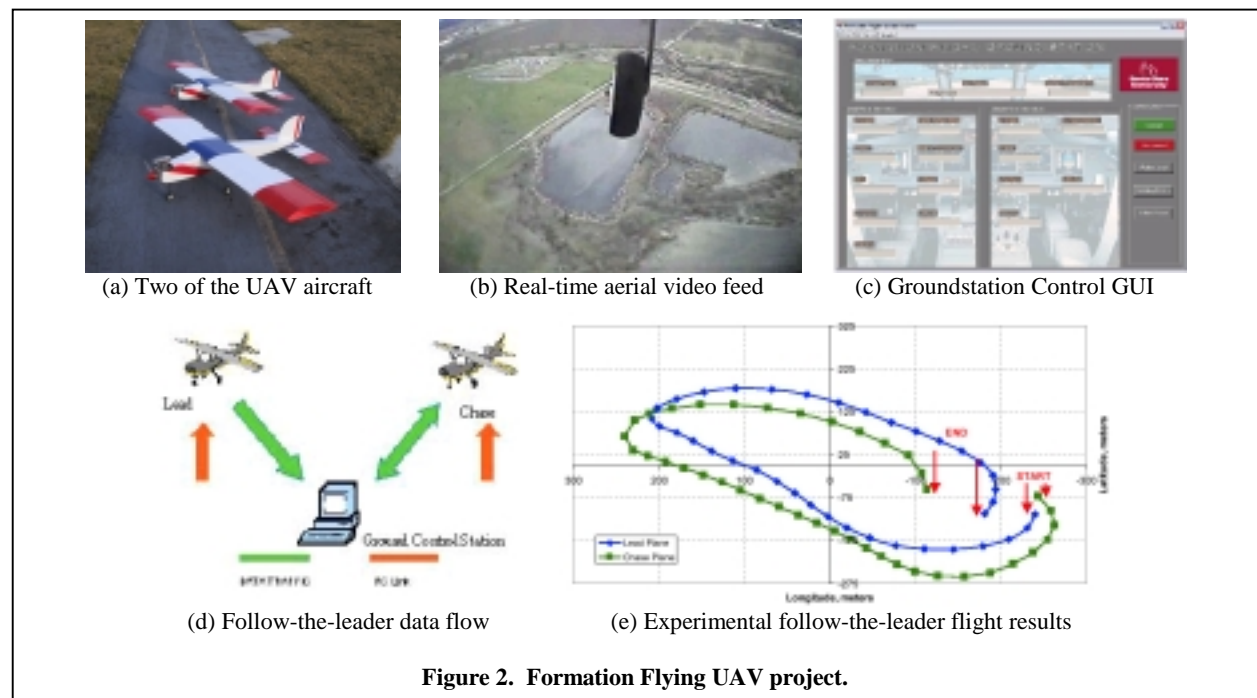
The development and use of these robotic systems serves as the keystone for the integrative nature of the SCU program. Overall, the mixing of engineers and scientists across a variety of educational levels and from a multitude of organizations creates a particularly stimulating environment for technical education, engineering innovation, and scientific discovery. Furthermore, the availability of multiple operational robots in several domains offers unprecedented opportunities for low-cost experimental research exploring issues in multi-robot system control and teleoperation.

2. Undergraduate Multi-Robot Projects

Over the past three years, a number of undergraduate projects involving multi-robot systems have been conducted. This section reviews three of these, spanning a wide range of programmatic characteristics.

A. Formation Flying Aircraft

During the 2003-2004 academic year, a team of three computer engineers developed a fleet of hobby-class aircraft and used them to demonstrate basic, automated follow-the-leader formation flying [3-4]. The team developed an embedded avionics suite consisting of a GPS receiver and other sensors, a microcontroller to collect and format this data, and a digital wireless communications link to broadcast flight data during operations. The team also implemented real-time video broadcasting through the incorporation of an on-board camera with servo-based tilt control and a separate long-range wireless video transmission system.

(a) Two of the UAV aircraft   (b) Real-time aerial video feed   (c) Groundstation Control GUI

(d) Follow-the-leader data flow   (e) Experimental follow-the-leader flight results

Figure 2. Formation Flying UAV project.

As part of this team's participation in the annual, international Unmanned Aerial Vehicle (UAV) competition sponsored by the Association for Unmanned Vehicle Systems International, the capstone team installed a Micropilot MP2028g autopilot system in one plane. Using this autopilot, the team demonstrated several capabilities required to be competitive in the competition; this included the ability to autonomously take-off and fly a pre-determined waypoint-defined route in order to image an unknown ground target. This team ultimately achieved a 3rd place finish in this international event, competing against several teams with established graduate programs in UAV systems.

This team, however, was motivated to go well beyond this level of capability. Intrigued by RSL's research program in multi-robot formations, the team exploited the capabilities of their autopilot in order to implement an automated follow-the-leader capability. With a human pilot flying a lead plane, position data from this plane would be continuously sensed and broadcast to the ground. A ground station application, developed by the students, filtered this data and generated the target waypoints for the chase plane. These waypoints were then transmitted to the chase plane's autopilot for execution. The chase plane's position was also sensed and broadcast to the ground for subsequent analysis and display. Overall, this team's outstanding work was awarded with a technical excellence award from the SCU Computer Engineering department and a Best of Session award in the SCU School of Engineering's year-end design conference.

B. Multi-robot Coordinated Navigation

The outstanding work of the 2003-2004 Formation Flying UAVs team attracted the attention of researchers at NASA Ames Research Center who were developing multi-UAV control algorithms and experimentally demonstrating them with larger scale aircraft. This, combined with an investment by RSL in several research-grade commercially available robots, led to an interdisciplinary 2004-2005 capstone project involving the development of a multi-robot rover testbed capable of testing possible UAV control algorithms. This project, known as the Decabot Testbed, consisted of developing a 7-robot system (soon to be 10-robot system, as the name suggests) of heterogeneous non-holonomic vehicles suitable for outdoor operation [5]. The robots use two commercial chasses, the Activmedia Amigobot (differential drive) and Pioneer (skid steering) robots. These commercial chasses provide robot-level closed loop velocity control, and they supply sonar and wheel encoder sensor data.

The capstone team equipped each robot with an avionics suite that include a WAAS-enabled GPS receiver, a digital compass, a long-range wireless communication system, and a distributed microcontroller network for on-board computation. In addition, a central control station was developed to a) provide an operator the ability to specify the desired motion of the cluster, b) collect and display robot state information sent via the wireless communication systems, and c) compute automatic system control actions via Matlab-based controllers. By the end of their project, the team was able to demonstrate simultaneous, centrally synchronized control of all of the robots. They also began to provide testbed services to a graduate student who had started to use the system to run experiments for his thesis. The 2005 Decabot student team won several of the SCU School of Engineering's top engineering awards to include the Best Computer Engineering and the Best Overall Interdisciplinary Project award in the School's senior design conference.

In the past year, the Decabot testbed has been used to support four experimental Masters theses in the cooperative control of mobile multi-robot systems [6-11]. Three of these projects were conducted by students on the original design team. The robots are currently a critical piece of the RSL multi-robot control research program. Three new graduate students have started research work targeting the use of this system, and significant technical extensions to the testbed are now underway as part of a new National Science Foundation grant.
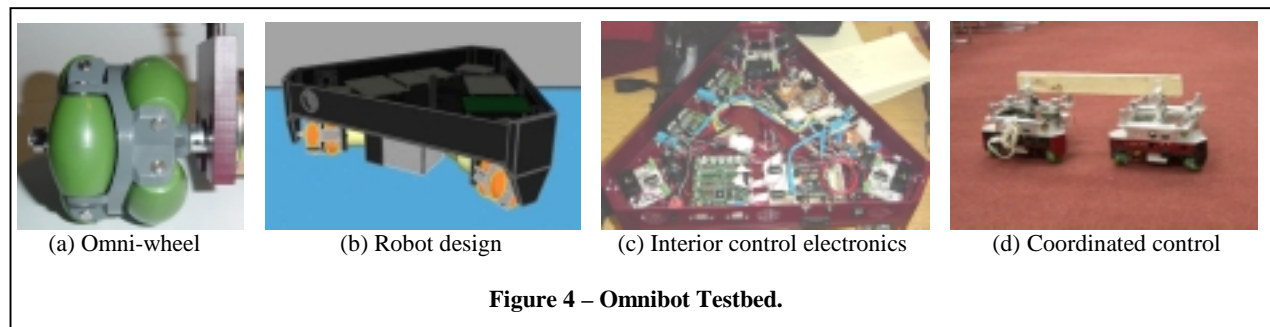

| (a) Robotic vehicles | (b) On-board components | (c) Off-board operator GUI |
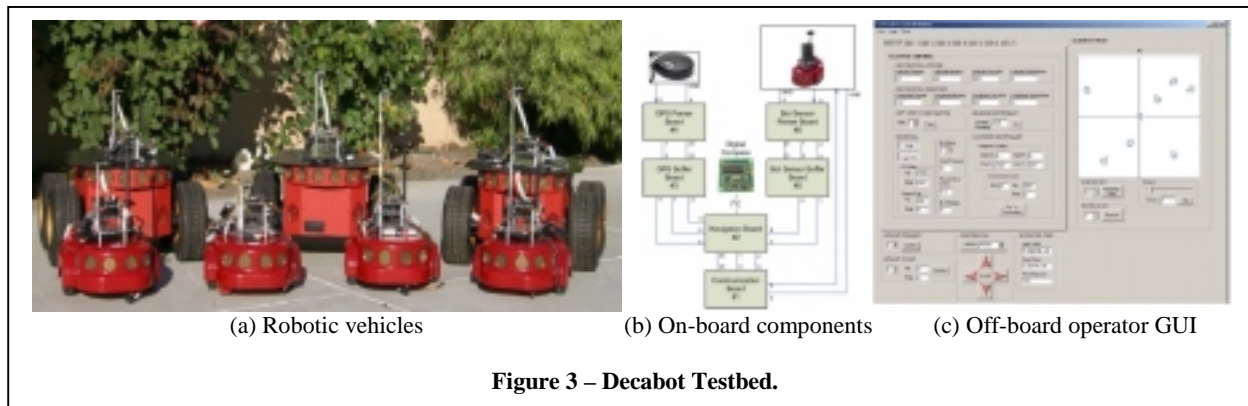
Figure 3 – Decabot Testbed.

C. Multi-robot Object Transport

During the 2003-2004 academic year, an interdisciplinary team of four students developed, from scratch, two identical "omni-drive" robots capable of independent translation and rotation [12]. The intent was for these robots to ultimately serve as a Lab testbed for graduate level research in multi-robot collaboration and formation control. Using commercially available "omni-wheels", the team developed a custom chassis and a complete set of motion control electronics. Both closed-loop velocity control and closed-loop position control were supported, with robot-level commands being converted on-board to wheel setpoints and with these setpoints controlled via industrial PID control circuits. At the end of their project, the team demonstrated complete holonomic motion and synchronized motion of the two vehicles. The outstanding achievements of this team included a technical excellence award from the SCU Computer Engineering department, top honors in the SCU School of Engineering's year-end design conference (based on a perfect score from the industry judges), and a Merit Award in the national Lincoln Foundation design competition.

An interdisciplinary capstone team during the following year developed mechanically compliant gripper assemblies for both robots, and used these assemblies to support experiments in multi-robot transport and manipulation of objects [13]. The team used a master-slave control strategy. The master robot executed a motion profile, and the slave robot moved in a coordinated by attempting to null position errors generated by the master robot pulling the object being transported. The implementation of this control system included the development of a distributed microcontroller network for sensing, communications, and robot interfacing. This team won a Best of Session award in the SCU School of Engineering year-end design conference and a Merit Award in the national Lincoln Foundation design competition.

In the past year, these robots have been used to support four experimental Masters theses in the cooperative control of mobile multi-robot systems [14-18]. One of these projects was conducted by a student on the original design team, and another project was conducted by a student who worked on a different SCU robotics project as an undergraduate. Like the Decabots, these robots are currently a critical piece of the RSL multi-robot control research program. In addition to supporting studies on the control of holonomic land rovers, they also serve as low-cost medium fidelity hardware-in-the-loop simulators for testing control approaches for RSL projects involving underwater robots, spacecraft, and airships.

| (a) Omni-wheel | (b) Robot design | (c) Interior control electronics | (d) Coordinated control |

Figure 4 – Omnibot Testbed.

3. Student Learning

These challenging and interdisciplinary nature of these projects provide ample opportunity for students to apply and extend their knowledge in a wide range of subjects spanning mechanical, electrical and computer engineering. As part of the engineering capstone experience, these projects are also designed to support a number of specific learning objectives. These include [19]:

- The ability to design systems, components, or processes to meet needs,
- The ability to function on multi-disciplinary teams,
- The ability to communicate effectively,
- The ability to use techniques, skills and modern engineering tools necessary for engineering practice.

In conducting these and dozens of other projects over the past six years, several aspects of these projects that significantly influence success have been identified. These include:

- Having a compelling application – the excitement of robotics, the cutting-edge nature of these particular projects, the creation of a system with long-term value, and the ability to make a significant contribution all provide critical motivation.

- Active project management – success in reaping long-term institutional rewards from undergraduate-designed and built projects requires a great investment in advising and mentoring the student team. The use of formal project management, systems engineering and concurrent design techniques also helps to increase the efficiency of conducting many such projects in parallel.
- Availability of resources – the projects reviewed here all required a thoughtful commitment of financial and infrastructure resources. The ability to ultimately leverage these projects in supporting graduate student research, the development of high-quality publications, and in attracting research grant money are critical elements of justifying the initial investments in advising time and institutional money.

4. Conclusion

In summary, SCU has developed a highly successful robotics-based undergraduate education program culminating in a capstone experience that provides rich opportunities for interdisciplinary design teams to develop exciting, real-world engineering systems. The multi-robot systems described in this paper are outstanding examples of the level of quality that these students are capable of achieving, given the proper motivation and learning environment.

Acknowledgements

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