AC 2010-1305: TEACHING MULTIDISCIPLINARY DESIGN TO ENGINEERING STUDENTS: ROBOTICS CAPSTONE

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Teaching Multidisciplinary Design to Engineering Students: Robotics Capstone

Abstract

Robotics Engineering (RBE) is a new undergraduate degree program at Worcester Polytechnic Institute (WPI). As of the fall semester of 2008, the program is the fourth largest discipline at the institution in terms of freshman enrollment. At the core of the curriculum are four signature courses called Unified Robotics I-IV. The educational objective of these courses is to introduce students to the multidisciplinary theory and practice of robotics engineering, integrating the fields of computer science, electrical engineering and mechanical engineering. In addition to taking these and other courses, it is a requirement that all WPI undergraduates, regardless of discipline, complete a senior-level project in their major field of study called Major Qualifying Project (MQP). This paper discusses the capstone design experience within the context of our new RBE degree program. Topics covered include the problem of teaching multidisciplinary design to senior engineering students working on solving real-world problems engineering design problems and a discussion of our capstone design evaluation criteria, particularly as it applies to a multidisciplinary program. Finally, learning outcomes specifically designed for the senior-design and sample projects completed by robotics engineering students that illustrate our approach to designing this new robotics engineering program at the undergraduate level are presented.

Introduction

Considering the fact that engineering students of 2010 will still be professionally active in 2050, their engineering education today should be broad enough for them to generate solutions to meet the new requirements of the global industry and society [1-3]. To achieve a smooth transition from academia to industry, there should be an agreement between the desired outcomes of engineering curricula and the desired attributes of an engineer defined by the industry. In other words, the graduates of engineering programs must have a set of basic skills to meet the needs of the industry and society. A good understanding of engineering science, a good understanding of engineering design process, a multidisciplinary perspective, excellent communication skills, high ethical standards, critical and creative thinking, an appreciation of the importance of teamwork, an awareness of economic, environmental and societal issues, and a desire for life-long learning are among the attributes forming the interface between the engineering education and the engineering practice [4,5]. In an attempt to build on this interface, engineering programs strive to meet the well-known ABET (a)-(k) criteria presented in Table 1.

One key component of providing a broad education is the multidisciplinary experience gained by working on projects that are open-ended and complex and attempt to provide solutions to practical real-world problems. This is why teaching multidisciplinary design to engineering students especially at the senior level has been the motivation for engineering educators to adopt innovative approaches within engineering curricula [6-9]. Excellent examples of industry sponsored or competition-driven capstone design projects are reported in the literature [10-13]. These open-ended and complex projects attempt to provide a solution to a practical real-world

Table 1: Criterion 3 for Accrediting Engineering Programs by ABET Engineering Accreditation Commission outlines a set of expected outcomes for engineering programs.

Criterion 3. Program Outcomes
Engineering programs must demonstrate that their students attain the following outcomes:
(a) an ability to apply knowledge of mathematics, science, and engineering
(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
(d) an ability to function on multidisciplinary teams
(e) an ability to identify, formulate, and solve engineering problems
(f) an understanding of professional and ethical responsibility
(g) an ability to communicate effectively
(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
(i) a recognition of the need for, and an ability to engage in life-long learning
(j) a knowledge of contemporary issues
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

problem. A majority of such problems require solutions which integrate sensing, computing and acting. Therefore, it is typical to see a multidisciplinary approach to capstone design bringing students from electrical and computer engineering, mechanical engineering and computer science. This allows students to be exposed to design problems outside of their own field.

Within the context of this real-world projects discussion, robotics as an engineering discipline is an interdisciplinary field of study which can be used to enrich and broaden engineering education; it promotes teamwork, technical competency, innovation and lifelong learning; more importantly, it proved to be an effective tool for improving the recruitment and retention of a diverse range of students [14, 15]. As such, Robotics Engineering is an excellent fit for the undergraduate engineering education of 2020 described in the NAE report titled *Educating The Engineer Of 2020* [3]. In fact, over the past several decades, robotics has evolved to become a rather diverse field covering a wide spectrum of applications ranging from assistive technologies to consumer robotics products, from complex industrial robots to humanoids. This variety provides opportunities for incorporating robotics into the undergraduate engineering not only in the form of coursework but also as research or capstone design experiences. As a result, students remain engaged in engineering design throughout their undergraduate curriculum. The interdisciplinary nature of robotics makes it suitable for capstone senior design projects that aim to broaden student expertise before they enter the engineering workforce. Therefore, a capstone design experience revolving around robotics can be used to enrich and broaden engineering education. It is also a good fit teaching multidisciplinary design not only at the high level but also at the subsystem requirements level.

An Overview of the Robotics Engineering Program at Worcester Polytechnic Institute

Robotics Engineering (RBE) is a new undergraduate degree program at WPI introduced in the spring of 2007 and administered by the departments of Computer Science, Electrical and Computer Engineering and Mechanical Engineering. As of the fall of 2008, the program is the fourth largest engineering program (among 11) at the institution in terms of freshmen enrollment. The B.S. program produced its first graduates in May 2009 and it is planned to seek ABET-EAC accreditation under general engineering criteria in the 2010-2011 academic year.

The RBE program objectives are to educate men and women to:

- Have a basic understanding of the fundamentals of Computer Science, Electrical and Computer Engineering, Mechanical Engineering, and Systems Engineering.
- Apply these abstract concepts and practical skills to design and construct robots and robotic systems for diverse applications.
- Have the imagination to see how robotics can be used to improve society and the entrepreneurial background and spirit to make their ideas become reality.
- Demonstrate the ethical behavior and standards expected of responsible professionals functioning in a diverse society.

These objectives are implemented, in part, through a series of four signature courses called Unified Robotics I-IV. The goal of these courses is to introduce students to the multidisciplinary theory and practice of robotics engineering, integrating the fields of computer science, electrical engineering and mechanical engineering. In addition to the Unified Robotics course sequence, the RBE program requires students to take digital circuits, embedded programming, statics, controls, object-oriented programming, software engineering, entrepreneurship and a number of technical electives.

In contrast to a theory-driven traditional engineering curriculum, the Unified Robotics courses start with the robot as a design platform and introduce the theory and principles of electrical and mechanical systems as well as programming and algorithms with applications to robotics.

The sophomore-level courses, Unified Robotics I and II (RBE 2001 and RBE 2002), emphasize the foundational concepts of robotics such as kinematics, stress and strain, pneumatics, circuits, operational amplifiers, electric motors and motor drive circuits, sensors, signal conditioning and embedded system programming using C language. The goal is to introduce students to the analysis of electrical and mechanical systems as well as the principles of software engineering. In both courses, the emphasis is on robotics applications, project-based learning and on the relationship among the electrical engineering, mechanical engineering and computer science disciplines as they apply to robotics. In combination, RBE 2001 and RBE 2002 provide a study of the foundations of robotics by integrating the fields of computer science, electrical engineering and mechanical engineering and prepare students for the advanced robotics courses.

The junior-level courses, Unified Robotics III and IV (RBE 3001 and RBE 3002), build upon the intuition that the students began to develop in the 2000-level courses. It is in these courses that the students actually begin to understand and appreciate the details underlying their 2000-level experience. These junior-level courses provide a much deeper theoretical coverage of robotics, including: kinematics and inverse kinematics, control systems, sensors, signals, reasoning with uncertainty, navigation, world modeling and planning. In these courses students no longer have pre-packaged hardware and software components; they now are introduced to interrupt-based programming, software system architecture, object-oriented design and in-circuit debugging.

It should be noted that all Unified Robotics courses are offered in 7-week terms with 4 hours of lecture and 2 hours of laboratory session per week. Further in concept with the long history of the WPI Plan [16], these courses emphasize project based-learning, hands-on assignments, and students' commitment to learning outside the classroom.

Capstone Design Experience

The RBE capstone senior design experience serves as the binding agent for the theory and practice learned in our core RBE courses and should demonstrate application of the skills, methods, and knowledge gained in the program to the solution of a problem that typically involves the design and manufacture of a robotic system. Further, our recent experience with robotics capstone projects indicates that student learning is drastically improved as the students are extraordinarily enthusiastic about their projects, working within multidisciplinary teams and communicating their "cool" robot projects to peers, faculty and representatives from sponsoring industries.

While our early capstone advising experience and project outcomes were highly successful, the above scenario poses a problem for teams of students that are not composed entirely of Robotics Engineering majors since it presumes that all project students will begin their capstone experience with the background provided by the multidisciplinary Unified Robotics I-IV courses. In general this has not proven to be the case, since it is very common for capstone design project teams to include students from other disciplines. Within the RBE program, robotic systems are viewed as solutions to problems using robotic technology – not as systems that contain an "ECE part," an "ME part," and a "CS part." In other words, even if teams consist of students from traditional disciplines, there needs to be a focus on how disciplines interact with each other and how system-level decisions must be made in a manner that considers the cross-disciplinary ramifications of the decisions.

It should be noted that the capstone project, as implemented at WPI, is equivalent to three courses (1/4 year) and, in general, is completed in three 7-week terms. There are no lectures or labs that accompany the project in comparison to most universities where the capstone project is completed as part of the normal student coursework. Students work independently on the projects with supervision of a faculty member. Students meet regularly with their advisor. A final project report detailing the process and the final product and a formal presentation to the entire school and professionals from industry during the Project Presentation Day are required. Upon completion of the project, the final reports and supporting documents become part of the university's library catalog and are made available online.

Examples of Capstone Projects

In order to illustrate our approach, we will consider three multidisciplinary capstone senior design projects called Major Qualifying Projects (MQPs) completed during the 2008-2009 academic year.

Robot Research Platform For Locomotion Through Granular Media

This project is commonly referred as sand-swimming robot or snake robot among RBE students and faculty (Figure 1). The motivation for the project was the need for a platform to perform experiments and understand the dynamics of locomotion through granular media such as sand. The project team consisted of two students, one from mechanical engineering and one from robotics engineering. The project tasks involved the mechanical design of each link and joint forming the robot, battery and motor selection, design and implementation of the peripheral electronics, and selecting the controller algorithm. The project received 2009 Provost’s Award in Robotics Engineering. Based on the responses to the MQP Presentation Evaluations completed by the faculty, industry representatives and students, this project demonstrated multidisciplinary design knowledge (with a rating of 4.8 out of 5.0).

Figure 1: Robotic research platform for locomotion through granular media

Hand-Eye Coordination in a Humanoid Robot:

Even though this project was more computer science oriented in nature, students were required to apply forward and inverse kinematics for robot manipulators and understand the controller for the humanoid robot Melvin (Figure 2). The project team consisted of 2 computer science and 1 robotics engineering students. Project tasks included integration of a vision system with the humanoid robot, image processing, and developing algorithms for hand-eye coordination for the robot in a dynamic environment. The project received the 2009 Provost’s Award in Computer Science. Based on the responses to the MQP Presentation Evaluations completed by the faculty, industry representatives and students, this project demonstrated multidisciplinary design knowledge (with a rating of 4.0 out of 5.0).

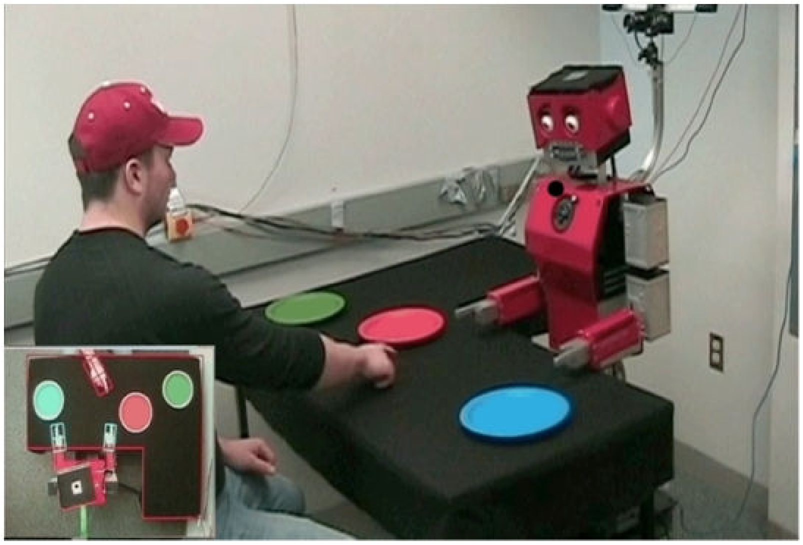

Figure 2: Hand-eye coordination in a humanoid robot

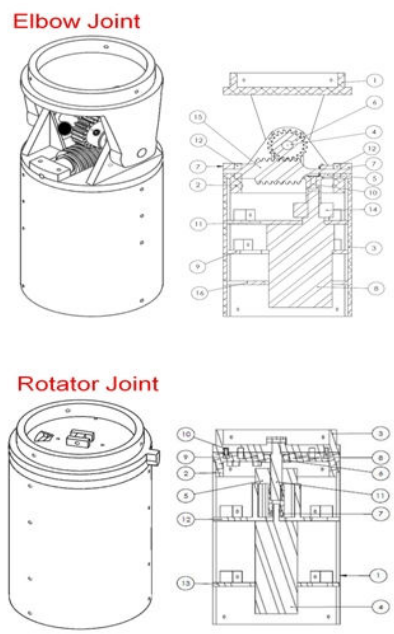

Figure 3: Low-cost manipulator joint design

Design of Low Cost Robotic Manipulator Joints:

In this project students were tasked to design low-cost, modular manipulator joints (Figure 3). The motivation for the project was to fill the gap between low quality hobbyist-type manipulator joints and high-precision, high-cost industrial ones. The project team was composed of one electrical and computer engineering and three mechanical engineering students. When they were first assigned to the project, the students only tackled the problems in the areas that they felt comfortable. As the project progressed, it was observed that everyone within the team had an understanding of the entire design since every student was required to understand the requirements and derived specifications for each subsystem of the entire robot and in some cases make design decisions not directly related to their major field of study. Based on the responses to the MQP Presentation Evaluations completed by the faculty, industry representatives and students, this project demonstrated multidisciplinary design knowledge (with a rating of 4.5 out of 5).

A common observation made by the faculty advisors in each of these capstone projects: It takes a great deal of time for the students to recognize the multidisciplinary nature of the project and the need to establish an understanding of the entire project rather than only their “part”. For example, the manipulator joint design project discussed above, the project was more than half complete before the mechanical engineering students felt comfortable talking about motor selection and specifications. On the other hand, it wasn’t until the end of the project that the electrical engineering student had developed only a basic understanding of the mechanical design. We believe that this is a problem if we want our students to be cross-trained and capable of tackling multidisciplinary real-world problems.

Capstone Preparation Course

In support of the multidisciplinary capstone nature of projects completed as part of the new Robotics Engineering program, a new course has been developed that confronts the issues associated with robotic system design directly. The course has been offered for the first time in the fall semester of 2009 as an RBE elective and it is discussed in a companion paper at this conference in detail. The course description is:

> **Robot System Engineering and Design**
>
> The designers of robotic systems start with a system requirement and must design the mechanical, electrical and software systems which must work together to achieve the goals of that system. Typically, parallel teams of engineers will work concurrently to create a working system within the time and budget constraints of the project, meaning that it is necessary to organize a project in such a way that parallel teams can work independently.
>
> This course explores the tools and techniques used to develop complex systems. The topics covered include: requirements development; system architecture and partitioning; requirements flowdown; functional and interface specifications; trade studies; system modeling and simulation; system integration; as well as design verification and validation.

Project Learning Outcomes

As with any course of study, student project team members are often required to achieve specific learning outcomes. For example, for generic capstone project work, it is desirable that the mentor work with the students to determine if the project "shows acceptable evidence of" economic considerations, safety considerations, reliability considerations, aesthetic aspects, analysis, synthesis, integration of previous course work, and experimental work. Different departments, majors, areas and topics may have other evidence based criteria to consider. Regardless, it is incumbent on the center advisor(s) to insure that all team members are aware of the criteria and that the students are directed along a learning path that will address the criteria. Although WPI has been focused on projects based education for well over thirty years it was only in 2009 that outcomes were approved for the capstone design (Table 2).

Table 2: Capstone Learning Outcomes

Students who complete a Major Qualifying Project will: (a) apply fundamental and disciplinary concepts and methods in ways appropriate to their principle areas of study (b) demonstrate skill and knowledge of current information and technological tools and techniques specific to the professional field of study (c) use effectively oral, written and visual communications (d) identify, analyze and solve problems creatively through sustained critical investigation, (e) integrate information from multiple sources, (f) demonstrate an awareness and application of appropriate personal, societal, and professional ethical standards, (g) practice skills, diligence, and commitment to excellence needed to engage in lifelong learning.

Assessment

Based on the project learning outcomes, faculty uses a variety of methods of measurement to collect data on the capstone design experience. We can divide the MQP assessment instruments into several categories.

- **MQP Report Review:** At regular intervals determined by the university administration, all programs undertake a significant review of the content and quality of that year's MQPs. Many of the outcomes are assessed, as well as the correlation between perceived quality and grade assigned.
- **MQP Presentation Evaluations:** In April every year all graduating students present their MQPs to their departments and the public. The RBE faculty evaluates every presentation using a standard form. The resulting data are mostly used to evaluate presentation skills.
- **Advisor's Evaluation of MQP:** Every MQP has a faculty advisor who provides an evaluation of every completed MQP. The resulting data are used to provide a view of how well MQPs are supporting outcomes.

To highlight the specifics of the assessment process, an example will be drawn from the ECE department as one of the RBE program sponsors since only a few capstone projects have been completed within the RBE program. Basically, the approach is two-fold. First, the faculty advisor(s) of a completed project are asked to fill out an assessment form on which the advisor notes to what extent the completed project team, and individual team members, addressed the specific ABET capstone consideration areas (economics, safety, …). Second, every other year two program faculty spend the summer reading and evaluating every single project report completed since the previous review. Factors are ranked on a scale of 1-5 where 1 is not at all or poorly done/not appropriate to 5 which is to a great extent or well done/ appropriate. The ranked factors include the following.

- the ABET factors (economics, safety, …)
- appropriateness of the grade assigned
- whether the documented work represented a full 9 credits of project activity
- the level and extent of design and analysis
- the quality of the documentation
- the quality of the figures, tables, data, etc
- whether experimentation and laboratory work was involved
- the quality and extent of the references

Finally, the Capstone Review Committee collect and summarize the oral presentation evaluations generated during project presentation day to assess the quality of the presentations, areas in need of work, and long term trends. Once the project reports have been read and analyzed, and the oral presentation reviews have been tabulated, a report is generated that summarizes the methods, data and observations, and makes recommendations for quality control and overall project program improvements. This review includes a comparison to previous reviews so that trends and problems can be identified, and the results of previously recommended improvements can be assessed. The data, summary report, and recommendations are presented and reviewed early in the next academic year so that actions can be taken to continue to improve the overall MQP experience.

Based on project evaluations and faculty feedback following observations can be reported about the Robotics Capstone:

- Robotics capstone serves as the binding agent in the new undergraduate degree program in Robotics Engineering offered at WPI since 2007.
- In nature, robotics projects are interdisciplinary and attract students from robotics, electrical and computer, and mechanical engineering as well as computer science programs.
- One common problem is that not all students from traditional programs (CS, ECE, and ME) feel comfortable stepping outside of their own fields of study when working in a multidisciplinary team.
- Since the new Robotics Engineering program emphasizes the multidisciplinary design process not only at the high level but also at the subsystem level through course projects early in the curriculum, they become an asset within a multidisciplinary team.
- Despite the heavy work load, the quality of the projects completed so far is a clear indicator that the capstone design experience in the new RBE program can be used effectively for teaching multidisciplinary design to educate the Engineers of 2020.

This year's MQP reviews will be done during the summer of 2010. The RBE faculty is currently working on adopting a more quantitative approach to assessing the MQPs.

Conclusion

This paper has presented an overview of the capstone experience within an undergraduate robotics education designed to provide a broad engineering education to meet the needs of the industry and society. The implementation of the projects illustrates the approach adopted by the faculty at the WPI to design a new robotics engineering program at the undergraduate level. Although most student learning take place outside the classroom by enforcing hands-on assignments and independent study, students remain passionate about robotics and are highly committed to the new RBE program. The robotics capstone experience has been a successful approach to teaching multidisciplinary design methodology.

Bibliography

1. NSF National Science Board, Moving Forward to Improve Engineering Education, 2007.
2. Innovate America, Council on Competitiveness National Innovation Initiative Summit and Report, 2005.
3. National Academy of Engineering, Educating the Engineer of 2020: Adapting Engineering Education to the New Century, 2005.
4. Boeing Co., "Desired attributes of an engineer", http://www.boeing.com/educationrelations/attributes.html
5. ABET Engineering Accreditation Commission, "Criteria for Accrediting Engineering Programs", 2009.
6. Dutson, A. J., Todd, R. H., Magleby, S. P., Sorensen, C. D., "A Review of Literature on Teaching Engineering Design Through Project-Oriented Capstone Courses", *Journal of Engineering Education,* 1997.
7. Miller, R.L., Olds, B.M., "A Model Curriculum for a Capstone Course in Multidisciplinary Engineering Design", *Journal of Engineering Education*, 1994.
8. Dombach, M., Knight, M., Rogers, C., "Teaching Seniors Through Developing Multidisciplinary Academies", Proceedings of CCLI Conference, The Power of Interdisciplinary/Multidisciplinary Courses and Curricula, 2007.
9. Hyman, B. L., "From Capstone to Cornerstone: A New Paradigm for Design Education", *International Journal of Engineering Education*, vol. 17, pp. 416-420, 2001.
10. Todd, R.H., Sorensen, C.D., Magleby, S.B., "Designing a Senior Capstone Course to Satisfy Industrial Customers", Journal of Engineering Education, 1993.
11. Paulik M. J., Krishnan M., "A Competition-Motivated Capstone Design Course: The Result of a Fifteen-Year Evolution", *IEEE Transactions on Education*, vol. 44, 2001.
12. Lumpp J., Jacob J., Smith S., Smith W., "BIG BLUE: A Multidisciplinary Capstone Engineering Design Project", *Proceedings of the 2006 ASEE Annual Conference & Exposition*, 2006
13. Padir T, Rasaiah J.P., Worden A., Richards A., Claus J., Horrigan T., Lucarelli A., "A portable robotic workcell: Building robotics technology partnerships", Proceedings of 2008 IEEE International Conference on Technologies for Practical Robot Applications, 2008.
14. Mataric M.J., "Robotics Education for All Ages", Proceedings AAAI Spring Symposium on Accessible, Hands-on AI and Robotics Education, 2004.
15. McKee G.T., "The Robotics Body of Knowledge", IEEE Robotics & Automation Magazine, vol.14 no.1, pp. 18-19, 2007.
16. The WPI Plan, http://www.wpi.edu/academics/catalogs/ugrad/theplan.html, Accessed on March 12, 2010.

Appendix A: MQP Presentation Evaluation Form (Completed by Faculty, Students and Industry Representatives)

ROBOTICS ENGINEERING MQP PRESENTATION EVALUATION FORM

D Term April 23, 2009

Project Title:

Student Names:

PART I: CONTENT	**NA**	**SD**	**D**	**Neutral**	**A**	**SA**
1. Objectives clear						
2. Motivation and impact discussed						
3. Approach and methodology clear						
4. Results analyzed and evaluated						
5. Appropriate experiment design & analysis						
6. Appropriate engineering design & analysis						
7. Independent learning demonstrated						
8. Multidisciplinary design experience demonstrated						
PART II: PRESENTATION						
1. Well organized						
2. Professional speaking behavior						
3. High-quality visual aids						
4. Understood & answered questions						

Appendix B: Project Outcomes and Assessment Survey (Completed by Faculty Advisors)

MQP Title:
MQP Code:
Students:
Advisor:
ADVISOR APPROVAL:
This Major Qualifying Project, on balance, is judged to satisfy the Capstone Design degree requirement and illustrates the following:

MQP DEMONSTRATES:
The following are characteristics which every engineering student should possess to some extent at the conclusion of his/her engineering education. The MQP provides a substantial opportunity for students to learn and/or to demonstrate these characteristics. Please indicate which of the following characteristics were demonstrated in this MQP.

( ) Appropriate Use of Math/Science/Engineering Knowledge
( ) Design of Experiments/ Data Analysis
( ) Design to Specifications
( ) Functioning Multidisciplinary Team
( ) Identify/Formulate/Solve Engineering Problem
( ) Ability to Communicate Effectively
( ) Sensitivity to Global/Societal Context
( ) Need for Life-time Learning
( ) Sensitivity to Contemporary Issues
( ) Use of Modern Engineering Tools and Techniques

MQP SHOWS ACCEPTABLE EVIDENCE OF:
The following items relate specifically to engineering design. As the major (capstone) design experience for most WPI students, the MQP is the activity where students would learn and demonstrate these characteristics. Please indicate which of the following characteristics were demonstrated in this MQP.

( ) Economic Considerations
( ) Safety Considerations
( ) Reliability Considerations
( ) Aesthetic/Ethical/Social Impact
( ) Analysis
( ) Synthesis
( ) Integration of Previous Course Work
( ) Experimental Work

COMMENTS: (particularly with regard to aspects which may not be apparent in the report)

Faculty Signature: ____

Date: ______________