UNIVERSITY OF DELAWARE

MASTER OF SCIENCE IN ROBOTICS

An interdisciplinary Masters of Science in Robotics administered by the Department of Mechanical Engineering

PROGRAM POLICY DOCUMENT

October 25, 2018

Contents

I. DESCRIPTION

The widespread availability of increasingly more capable and miniaturized, yet inexpensive off-the-shelf computational and sensing devices, the explosive increase in available data, in conjunction with the advancement and resurgence of algorithmic techniques, has lead to a surge in interest and a boom in robotics applications, ranging from drones, to automated vehicles, to autonomous driving. This interdisciplinary Master of Science in Robotics (MSR) program is answering the societal, government, and industry need for specialized education in this field. By emphasizing both theory, as well as critical engineering implementation aspects of robotics, the MSR program is designed to meet the needs of both professionals seeking advanced training, as well as scholars who want to start an exploration of the field through structured, guided instruction. Upon completion of the MSR program, a graduate is expected to have basic knowledge of *both* robotics fundamentals from different engineering disciplines *and* some skills associated with the development and deployment of robotic devices in real-world environments. The MSR program is flexible enough to be completed in 18 months, and it can incorporate research, or specific supervised project-based activities in the curriculum. These are some of the features that can make it attractive to local industry or government organizations interested in investing in improving the skills of their workforce, and for recruiting graduates of this program.

The program builds on some of the unique strengths, resources, and expertise that can be identified across the UD campus, to offer a higher education and professional training opportunity that cannot be easily replicated in the mid-Atlantic region. Students will be introduced to robotics from a cyber-physical systems perspective, through a curriculum that integrates dynamics, control, sensing, computation, software design, optimization, and machine learning. Concurrently, students will be exposed to implementation challenges of turning theory and algorithms into a functional system that is robust enough to be deployed and be functional under real-world conditions. In fact, one of the unique aspects of the MSR program is in leveraging the campus-wide facilities, expertise, and existing faculty collaborations, to expose its students within the normal curriculum, to aspects of implementation and utilization of robotic systems in *air, land, and sea.*

The proposed is a dual-track program, with one track being a course-based, non-thesis engineering masters degree, which allows for its students to interact with a partnering external organization, public or private, to experience workplace project-based activities for academic credit under the supervision of faculty participating in the program. This is made possible through the Graduate Student-Industry Partnership (GSIP) mechanism created within the Department of Mechanical Engineering, that utilizes graduate-level independent study over a one or two semester period. The second track is thesis-based, substituting 6 credit hours of course-work for a masters thesis.

The degree thus requires the completion of a total of 30 academic credit hours, 6 of which can be thesis credits, and which can be accomplished in as little as $1\,\frac{1}{2}$ years (18 months) with appropriate course-load. The MSR program's curriculum consists of a core of six (6) required courses, and four (4) electives. The latter are selected from an approved list of graduate courses and are designed to provide the opportunity for specialization in particular academic subareas such as control, estimation, optimization, or machine

learning.

A course sequence that can make up such a meaningful two-year robotics curriculum plan can already be put together with courses that are currently offered, or are scheduled to be offered on a regular basis in the very near future, by existing faculty. The aforementioned areas are also among the ones that can be made immediately available currently. With the anticipated growth of the participating units, and the commitment of the University in continuing recruitment in the field, it is expected that the concentration options will increase through the addition of more technical elective courses.

II. RATIONALE AND DEMAND

II.A Institutional factors

The mission of the University of Delaware is to *cultivate learning, develop knowledge and foster the free exchange of ideas.* In addition, the University is committed *to increasing and disseminating scientific, humanistic and social knowledge for the benefit of the larger society.* In this context, the MSR program is aligned with, and supports the mission of the University, by disseminating cutting-edge scientific knowledge in an interdisciplinary field of significance to the broader U.S. economy, and educating a specialized workforce that is expected to be responsive to current and near-future national and global employment trends.

The MSR program is a natural consequence of the establishment of a collaborative campus-wide network between faculty who are active in the general area of systems, and the convergence of ideas and goals of this academic subcommunity. The MSR program is likely to strengthen those links, connect students from diverse backgrounds and offer them interdisciplinary educational experiences, increase the opportunities for collaboration, and align existing research and educational activities across different academic units.

II.B Student demand

Figure 1 shows the growth of a comparable robotics masters program at Carnegie Mellon University over the past decade (see Table 2 on benchmarking data). CMU has kept its admission cap relatively constant — one possible reason could be infrastructure capacity — yet the application data suggest a steadily growing, if not accelerating, demand.

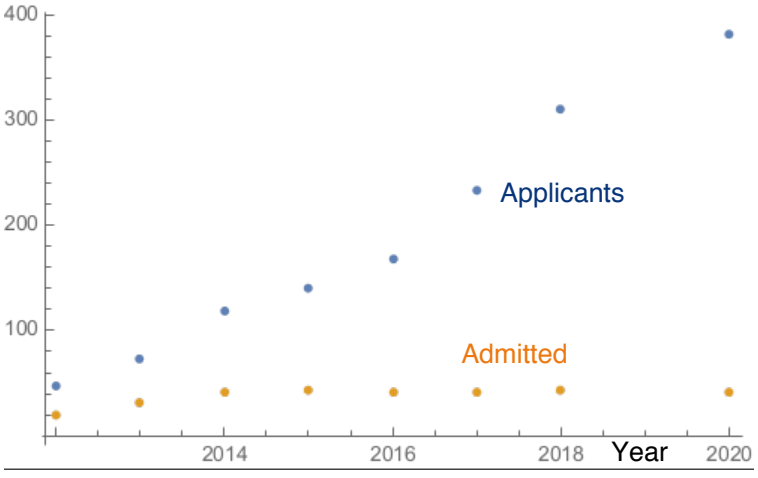


Figure 1: Growth of the masters program in "Robotics System Development" at Carnegie Mellon University from its inception until now. With a steady enrollment of no more than 50 students, the program's its admission rate is approaching 10%.

The data in Fig. 1 is not the exception. Although concrete information about demand for related programs is not readily available for comparison, a recently launched robotics program at the University of Michigan, part of the school's new Robotics Institute, has enjoyed similar market demand, reaching an approximate $1 \div 10$ admittance ratio with an average of 14 students in the program.

Based on this data, and the historical averages of the Department of Mechanical Engineering masters student population with expressed interest in robotics and control, we project that with the appropriate resources and infrastructure, the MSR program student cohort can at steady state match in size the current University of Michigan average. In lieu of a detailed market study, the Department of Mechanical Engineering has graduate enrollment data that suggest that an enrollment target of 15 students per year for the MSR program may not be unreasonable. Indeed, as Table 1 indicates, there is a robust interest in robotics and control within the pool of Master of Science in Mechanical Engineering (MSME) applicants in the recent years. While the creation of this new program could possibly draw some of these applicants out of the MSME pool, the MSR program's interdisciplinary nature and its capacity to recruit more students than just those with mechanical engineering background, makes it is more likely that the combined applicant pool for both programs will significantly increase.

Application year	Number of MSME applications	Number of applicants with interest in robotics	Percentage % of applicant pool
2015	33	13	39%
2016	94	40	43%
2017	96	42	44%
2018	59	33	56%

Table 1: MSME historical enrollment data suggest sustained interest of graduate program applicants in robotics and control.

The MSR program can be launched with existing or already planned courses. The majority of the courses (required and electives) that can form the first program curriculum are offered in an on-campus format. Several of the instructors involved in teaching them are in the process of bringing on-line content; however the availability of the *whole* program in a fully-fleshed online platform that will better serve part-time, currently employed, and non-traditional students will take time. In the meantime, the needs of this student segment will be addressed through existing mechanisms that allow remote participation in instructional activities (e.g. through UDCapture).

II.C Demand and employment factors

The graduates of the MSR program are expected to be sought after by private industry as well as government organizations. This is not speculation; in fact, both industry (e.g. Boeing, Siemens, Mathworks, Ocean Infinity, InDepth) and government (ARL/APG) has been continuously approaching participating academic units and individual faculty expressing interest in recruiting graduates with relevant training and expertise. In addition, there is increasing genuine interest by the public for education and training in the field of robotics nationally, and the State of Delaware currently does not offer any opportunities for graduate-level education in the area that can appeal to both professionals and scholars alike.

II.D Regional, state, and national factors

Robotics masters programs, typically at the graduate level, have started to appear at an increasingly frequent rate nationally. CMU and Penn were among the first institutions to offer such programs, and have been particularly successful. Often, such programs appear under the auspices of a college or university-level

dedicated center or institute (e.g. CMU, Penn, UMD). Table 2 presents data for comparison from a number of similar programs that were reviewed nationwide, across the spectrum of US News and World Report (USNWR) ranking: University of Pennsylvania (Penn), Carnegie Mellon University (CMU), Johns Hopkins University (JHU), University of Maryland (UMD), University of Michigan (UMich), and Worcester Polytechnic Institute (WPI).

School	Applicants	Enrolled	Tuition $/credit	Credits	Affiliated Departments
Penn			$\approx 1\,808$	30	CIS, ME, ESE
CMU	382	42	$\approx 2\,400$	≈ 20	CS, ECE, ME, PSYCH, MATH, ENTR
JHU			1 791	30	CIS, ECE, ME
UMD			979	30	AERO, ME, ECE, CS
UMich	325	16	2 700	30	AERO, ECE, ME, CS, ENTR
WPI			1 513	30	ME, ECE, CS

Table 2: Benchmarking study on existing related programs.

The MSR program is unique in that it blends theory with application of robotics technology in three different domains: air, land, and sea. As a result, our students will be exposed to a much broader and complete range of problems and solutions, will get more experiences, and will thus be able to maintain a broader perspective on the strengths, limitations, and potential of state-of-the-art robotic technology. This is particularly important since often established practices in one domain can be adapted and transferred to offer new solutions in another domain. We anticipate that the incorporation of applications of robotics technology will help to distinguish our program from competitors and enhance the attractiveness of our program to potential applicants.

In addition, there is particular interest by industry to be able to recruit locally, since recruitment and retention can be in general higher. Therefore, potential employers identified in Section II.C as well as others in the broader mid-atlantic region including Maryland, Pennsylvania, New Jersey, District of Columbia and Virginia, will benefit from the availability of highly skilled and trained local workforce.

II.E Other strengths

Faculty members with research interests in the general area of systems, across the UD campus, have been organically developing a professional network for collaboration, exchange of ideas and resources, and graduate student co-supervision. Currently, this network extends from Engineering, to Earth Ocean and Environment, to Agriculture, and to Health Sciences. This breadth of application domains, expertise, and experiences brought together through this organic cooperative effort is very hard to replicate in other institutions, can be leveraged more fully as the program grows and new elective courses are added into the curriculum, and new faculty members get involved.

In addition, UD is distinct among many other peer institutions in its ability to physically deploy mobile robotic devices in the three key domains: air, land, and sea. For the latter, UD can leverage the Lewes campus facilities and utilize the fleet of vessels available through the School of Marine Science and Policy, bringing together marine scientists with control engineers and computer scientists in efforts to automatically map the sea floor, monitor marine species populations, and search for submerged objects. On land, engineering faculty collaborating with colleagues in the College of Agriculture and Natural Resources have been making strides in field automation for the purposes of maize research, while collaborations with investigators from the College of Health Sciences have pioneered new methods for adult and pediatric motor rehabilitation. And in the air, Engineering faculty have been exploring autonomous indoor flight with specialized hardware and software and across different scales, while collaborators in Earth Ocean and Environment have been

deploying drones to map study beach erosion and marsh habitat health. This wealth of experiences, research expertise, and opportunities for independent studies and projects, can and should be transferred to students. The MSR program leverages this strength by offering concrete opportunities for applied and field-robotics projects, which can complement and balance more theoretical classroom instruction.

Indeed, the academic units currently participating in this program have agreed to make some of these resources available (see Appendix C). For example, the Faculty Director of the new Maker Gym and Idea Network, intends to help opening this unique space for project team-work in the context of robotics, and thus contribute in strengthening the MSR program's applied component.

III. ENROLLMENT, ADMISSIONS AND FINANCIAL AID

III.A Admission requirements

The requirements for admission to the MSR program are the following:

1. A baccalaureate degree in engineering or in a closely affiliated field of science or mathematics from a regionally accredited institution is required, with an undergraduate cumulative grade point average in engineering, science and mathematics courses of at least 3.0 on a 4.0 scale—or comparable to that ratio, for international degrees that use a different scale. Applicants with degrees in other disciplines may be admitted with provisional status and may be required to complete prerequisite courses that are deemed necessary for appropriate preparation for courses in the program. The GPA restrictions mentioned above apply also to applicants with academic background outside the traditional science and engineering disciplines.

2. A minimum combined Quantitative and Verbal score of 308 (1200) on the Graduate Record Examination Aptitude Test (GRE). Waivers may be considered on a case-by-case basis, and documented approval by the Department of Mechanical Engineering's Admissions Committee.

3. International applicants must demonstrate a satisfactory level of proficiency in the English language, if English is not their first language. International students are required to have a TOEFL with a minimum of 100 on the IBT and a speaking score of 20, or an IELTS with a minimum score of 6.5 with no individual sub-score below 6.0 on the IELTS alternative. TOEFL scores more than two years old cannot be considered official.

Candidates are required to provide the following additional documents, as part of their application package:

1. Three letters of recommendation from former teachers or supervisors.

2. Resume.

3. Statement of Purpose.

Admission to the graduate program is competitive. Those who meet the stated requirements are not guaranteed admission, and those who fail to meet all requirements are not necessarily precluded from admission if they present other appropriate and relevant strengths. The application window is from January 31st to July 31st, with priority given to early applications.

III.B Student expenses and financial aid

Students enrolled in the MSR program are responsible for all tuition, fees, and living expenses associated with participation in the program.

IV. CURRICULUM SPECIFICS

IV.A Institutional factors

Graduates of the MSR program earn a Masters of Science. The requirements and structure of this degree are modeled after those of the existing Masters of Science in Mechanical Engineering, which requires 30 credits of graduate coursework with the option of a thesis substituting for 6 course credits. Thus the amount and nature of academic effort required for the proposed degree is directly comparable to a similar existing degree in the same administering department.

Students who are in a PhD program at the University of Delaware may be able to add the Master of Science in Robotics to their degree, with their advisor's approval and accordance to the University policies for transfer of credits and change of classification.

IV.B Proposed curriculum

The MSR program involves a total of thirty (30) credit hours, spread over a period of 18 to 24 months (four semesters). A recommended course sequence, which distinguishes required from elective courses, is given in Table 3. The courses listed in Table 3 which are color-coded and typeset in italics are elective courses; the remaining ones are required courses for the degree. A student is therefore required to take six (6) required courses, and has the option of selecting four (4) more courses out of the list of approved graduate electives.

Table 3: PROPOSED TWO YEAR CURRICULUM MATRIX

		FALL		SPRING
YEAR 1		CISC 621 (Algorithms) MEEG 621 (Linear Systems)		MEEG 671 (Intro to Robotics) MEEG 678 (Autonomous Driving)
	choice of	*MEEG 620 (Dynamics)* *CISC 681 (Artificial Intelligence)*	*choice of*	*MEEG 677 (Intro to Estimation)* *CISC 684 (Machine Learning)* *MEEG 698 (Optimal Control I)*
YEAR 2		CISC 642 (Computer Vision) MAST 632 (Environmental Field Robotics)	*choice of*	*MEEG 829 (Nonlinear Control)* *MEEG 890 (Nonlinear Programming)*
	choice of	*MEEG 894 (Multivariable Control)* *MEEG 877 (Sensing and Estimation)* *MEEG 895 (Game Theory)*		

MAST 632 will provide a culminating educational experience in the MSR program, offering opportunities for integration of acquired knowledge, critical thinking and synthesis.

The course sequence of Table 3 is designed to allow for the completion of the degree within four (4) semesters with a maximum course load of three (3) courses per term. In principle, students pick one elective per semester to complete the total elective credit hour requirement of four (4); however, ambitious students can choose to enroll in more than one (1) elective per term, and complete their degree in eighteen (18) months.

The required and elective courses are arranged in a conceptual temporal sequence in Table 3 that is academically reasonable from a standpoint of relevance, technical background, and prerequisite material. However, the sequence itself is not binding; with the exception of required courses, and depending on their prior academic background, students may select a different collection of elective courses from what is shown in Table 3. It is anticipated that as the MSR program grows, the approved elective course list will evolve. The Executive Committee will be responsible for maintaining the list of approved electives. Under certain circumstances, students may still be permitted to select a course outside the approved electives list, but only with the documented approval of the Executive Committee, after filling out a course substitution form.

Brief descriptions for the courses appearing in Table 3 are provided below:

CISC621 Algorithm Design and Analysis: Emphasis on developing expertise in the design and analysis of algorithms. Equal importance given to techniques and specific algorithms. Particular topics include advanced data structures, graph algorithms, disjoint set manipulation, sorting and selection, amortized analysis, NP-completeness, and matrix and polynomial multiplication.

MEEG621 Linear Systems: State-space analysis of linear dynamical systems. Solution of state-space equations, and analysis of structural system properties based on eigenvalues and eigenvectors. Similarity transformations and decompositions. Lyapunov stability. Observability and controllability. State feedback control design.

MEEG671 Introduction to Robotics: Topics include: rigid motions and transformations, forward kinematics, Denavit-Hartenberg representations, inverse kinematics, velocity kinematics, dynamics, independent joint control, multivariable control, force control.

MEEG678 Introduction to Autonomous Driving: This course considers problems in perception, planning and control and their systems-level integration in the context of self-driving vehicles through an open-source curriculum for autonomy education that emphasizes hands-on experience, integral to the course. Students collaborate to implement concepts covered in lectures on a low-cost autonomous vehicle with the goal of navigating a model town complete with roads, signage, traffic lights, obstacles, and pedestrians.

CISC642 Introduction to Computer Vision: An introduction to the analysis of images and video in order to recognize, reconstruct, model, and otherwise infer static and dynamic properties of objects in the three-dimensional world. Studies the geometry of image formation; basic concepts in image processing such as smoothing, edge and feature detection, color, and texture; segmentation; shape representation including deformable templates; stereo vision; motion estimation and tracking; techniques for 3-D reconstruction; image registration methods.

MAST632 Environmental Field Robotics: An experiential course in the use and application of advanced environmental robotic systems. Emphasize a hands-on approach encompassing examination of platform design, sensors, navigation, mission planning, communication, and data analysis and interpretation.

MEEG620 Intermediate Dynamics: Reference frames, angular velocity, linear velocity, angular acceleration, linear acceleration, multibody systems, inertia properties, kinetic energy, equations of motion, generalized d'Alembert's principles, numerical integration, computer simulation.

CISC681 Artificial Intelligence: Programming techniques for problems not amenable to algorithmic solutions. Problem formulation, search strategies, state spaces, applications of logic, knowledge representation, planning and application areas.

MEEG 677 Introduction to State Estimation: The course covers the mathematical fundamentals of estimating the state of a dynamical system. It reviews basic concepts in linear systems, Bayesian estimation, and minimum mean-square estimation, followed by the introduction of the standard Kalman filter in both discrete-time and continuous-time formats. The course examines extensions of the Kalman filter that include the extended and unscented Kalman filters, as well as the H-infinity filter.

CISC684 Introduction to Machine Learning: Development of methods to learn to solve a task using examples. Explore different machine learning algorithms/techniques and discuss their strengths and weaknesses and situations they are or are not suited for.

MEEG698 Stochastic Optimal Control: The course covers the basic models and solution approaches for sequential decision making problems under uncertainty (stochastic control). The course will provide a unified treatment of the subject, suitable for a broad engineering audience.

MEEG894 Linear Feedback Control Design: This course integrates classical and modern approaches to feedback control into a powerful and insightful design and analysis methodology. The primary emphasis is on the implications that the mathematical equations have on design, rather than on their derivation. A major focus of the course is on multiple-input-multiple output (MIMO) systems; however, many new and useful results from single-input-single output (SISO) systems are also reviewed.

MEEG877 Sensing and Estimation in Robotics: This course consists of two main parts: (i) advanced nonlinear state estimation and (ii) sensor modeling and fusion. It emphasizes the application of estimation theory to mobile robot motion estimation and path planning, map representations, map-based localization, simultaneous localization/mapping (SLAM), and multi-robot cooperative navigation.

MEEG895 Game Theory and Mechanism Design: The course covers the basic models and solution approaches in problems that involve interactions among strategic agents distilling the key results in game theory and mechanism design. While game theory is concerned with analysis of games, mechanism design involves designing games with desirable outcomes.

MEEG829 Applied Nonlinear Control: Review of analysis of nonlinear dynamic systems. Qualitative behavior, differences compared to linear systems. Existence and uniqueness of solutions. Lyapunov stability theory and advanced stability analysis. Selected topics on control design for nonlinear systems.

MEEG890 Nonlinear Programming: Fundamentals of nonlinear optimization theory and methods. The course will provide a unified analytical and computational approach to nonlinear optimization problems covering a range of topics including methods for unconstrained optimization, constrained optimization, and convex analysis.

V. RESOURCES AVAILABLE

V.A Learning Resources

V.A.1 Scope and quality of available resources

In addition to library-specific resources, addressed explicitly in the following section, the University already offers some physical and cyber learning infrastructure that can directly support the proposed program. The Maker Gym and Idea Network (see letter in Appendix C) will offer physical space and resources for design and prototyping, and through the MAST 632 course the School of Marine Science and Policy (see Appendix B) will offer opportunities for field deployment of robotic vehicles, especially aerial, surface, and underwater platforms. Specifically for the MAST 632 course, the educational utilization of drones for outdoor deployment is already federally and institutionally licensed; other courses will touch upon programming and testing of aerial vehicle technology in computer simulation and indoors.

The CISC 621 course on Algorithms, as well as the CISC 684 on Machine Learning are popular courses with high demand. The MSR program will obviously increase this demand as it has these courses as required courses for the degree. To alleviate some of this pressure why The envisioned enrollment target for the MSR program is capped at 15 students in part because of the desire to alleviate this anticipated pressure. However, as the Department of Computer and Information Sciences is already planning on increasing the number of available sections for these popular classes, it is conceivable that we should be able to raise this enrollment cap in the near future.

Art Trembanis, the current instructor of MAST 632, is also the faculty director of the new Maker Gym and Idea Network which is currently under construction at the east portion of Pearson Hall and is scheduled to be completed in the Spring of 2019. Our intention and desire is to leverage this new facility in the context of team-based hands-on design and experimentation projects for the students in this program. In addition to hardware and instrumentation components available to the program's course instructors and which can be utilized for classroom instruction, students in this program working in teams should be able to design, build, and deploy their own robotic prototypes.

Finally, the College of Engineering IT team, working together with mechanical engineering faculty, have configured and can offer 25 pre-installed and configured (turn-key) implementations of an industry-standard open source software development and physics-based simulation environment (robot operating system (ROS)), which the students in this program will be utilizing throughout the curriculum. As an open-source platform, ROS can be used by any student on their own devices; the aforementioned pre-installed configurations will simply offer students without any substantial programming and system administration background the opportunity to utilize the environment without the hassle of having it installed and configured on their own computers.

Table 4: Faculty involved in the proposed program as instructors of required and elective courses, and their specialization.

Name	Rank	Specialization	Appt.	Degrees	Dept.
Herbert Tanner	Professor	multi-robot systems	full-time	BS-ME, PHD-ME	MEEG
Ioannis Poulakakis	Assoc. Professor	legged robots	full-time	BS-ME, PHD-ECE	MEEG
Guoquan Huang	Asst. Professor	estimation	full-time	BS-ECE, PHD-CS	MEEG
Andreas Malikopoulos	Asst. Professor	decentralized control	full-time	BS-ME, PHD-ME	MEEG
Arthur Trembanis	Assoc. Professor	oceanography	full-time	BS-OC, PHD-MS	MAST
Christopher Rasmussen	Assoc. Professor	computer vision	full-time	BS-CS, PHD-CS	CISC
Vijay Shanker	Professor	machine learning	full-time	BS-PH, PHD-CS	CISC
Valery Roy	Assoc. Professor	nonlinear dynamics	full-time	MS-ME, PHD-ME	MEEG

V.A.2 Library assessment

A formal assessment regarding the ability of the University of Delaware's Library to support this proposal is included in the proposal's Appendix.

V.B Faculty / Administrative Resources

Robotics is inherently an interdisciplinary field that brings together mechanical, electrical, and computer engineering and science. The instructors of the courses that make up the proposed curriculum cover all the aforementioned knowledge domains. Indeed, and irrespective of home department, program instructors come with degrees in all three disciplines. In addition, this group of domain experts is paired with field scientists who are end-users of robotic technology, thus exposing the students in this program to challenges and opportunities on both sides. This broader experience is critical for bridging and closing the loop between theory and practice, enabling the graduates of this program to have impact.

Faculty listed in Table 4 include some leaders in the field of robotics: Tanner and Poulakakis have been awarded the NSF CAREER Award; Huang has been awarded the NSF CRII Award; Tanner and Malikopoulos have recently been elected ASME Fellows.

VI. RESOURCES REQUIRED

VI.A Learning resources

For the basic implementation of the MSR program as outlined in this proposal, all necessary learning resources are already in place. For the program to thrive, be able to compete favorably for the best incoming students, and grow to be one of the premiere such programs nationally, some additional facilities, equipment, and computational infrastructure will definitely help. In addition to the Maker Gym space, which will be a shared core facility on main campus, a dedicated and modern space that would allow indoor deployment, testing, and experimentation on small-to-mid-scale ground and aerial robotic vehicles and can be show-cased when advertising the program, would certainly be beneficial. Furthermore, although basic computational ROS infrastructure for robotic software development and simulation of 20-25 seats has been put in place in the College of Engineering computer pods by Engineering IT and faculty from Mechanical Engineering, this facility is shared for a variety of other purposes, and as the MSR program grows, it is anticipated that competition will be generated for the pod seats. Thus a dedicated computer lab where the ROS infrastructure can migrate and be offered as a resource, not just to MSR students but to the whole campus, is expected to contribute to the success of the program.

VI.B Personnel resources

No additional faculty positions are required for the basic implementation of the MSR program. All courses displayed on Table 3 are, or will be taught, by existing faculty in the Department of Mechanical Engineering, the Department of Computer and Information Sciences, and the School of Marine Science and Policy.

In consultation with potential industry and government agencies who could be potential employers of our future graduates, some additional robotics-related specialties have been identified to have potential of contributing and improving the educational experience of students. These include robot design and hardware/software integration, adaptive materials for robotic applications, and wireless communications. Toward this end, there is potential for program expansion and incorporation of additional existing and emerging resources within the College of Engineering and across campus. Specifically, in the former area, a current faculty search in Mechanical Engineering is including the topic among the areas of interest; for adaptive materials, there may be opportunities for contributions from some newly hired faculty within the College of Engineering (e.g. Dr. Orazov–CHEG, Dr. Wang–MSEG); and in the latter area, the graduate catalog already includes an upper-level graduate elective ECE course on the subject which has not been taught in the recent past, but could potentially be revived.

VI.C Budgetary needs

The program is designed to be self-sustainable; in fact it is expected to generate revenue through graduate student tuition. The standard rate for graduate tuition will initially be at $ 1,827 per graduate credit.

However, similarly to the existing Masters of Science in Mechanical Engineering, a request will be made to bring it to the level of the approved reduced rate of $ 1,100 per credit, which will enable the program to be particularly competitive compared to its regional competition (see Table 2). Still, at this approved reduced rate, the program can bring a total per student tuition revenue of $ 33,000. Assuming an admission steady-state of 15 students per year, and based on the curriculum plan of Table 3 this number translates to tuition revenue generation of $ 297,000 per year.

The proposed program can thus be sustained with resources that are already committed by the participating academic units. No additional faculty lines are necessary for the basic implementation of the program as described in this proposal, although the inclusion of new graduate electives and the revamping of required courses will definitely benefit it, and allow it to grow. Growth can also will be facilitated with lines for teaching assistants, especially for those courses in the program's curriculum that involve project-based instruction and design. It is also conceivable that as these design-related teaching activities intensify, some relatively small funds will be have to be set aside from tuition revenue for consumables.

VII. IMPLEMENTATION AND EVALUATION

VII.A Implementation plan

The MSR program is modeled after the existing Masters of Science in Mechanical Engineering. The MSR degree can be pursued under either a Thesis Option, or a Non-Thesis Option. The program is designed to provide a balanced exposure to several aspects of robotics science and engineering, including automatic control, artificial intelligence, perception and estimation, design, and optimization. Students should be able to complete all degree requirements, including the thesis if chosen, in 18 to 24 months of full-time study.

No later than two years after the MSR program is established, a request will be made through the formal approval process so that the MSR degree may also be pursued as a 4+1 BS/MS masters degree As it is typically done, this will involve the completion and submission of a transfer of credit form and a change of classification form. With its current curriculum composition of required and elective courses, it is possible that undergraduate students can use up to two (2) of their bachelor's graduate-level technical electives (e.g., MEEG 620 and MEEG 621) toward the course requirements for the proposed degree. As the MSR program expands and more graduate electives are being approved, the opportunities for completion as a 4+1 BS/MS degree are expected to increase.

VII.A.1 Program administration

The program will be administered by the Department of Mechanical Engineering. The administration and oversight of the degree will be facilitated by an Executive Committee reporting to the Chairperson of the Mechanical Engineering Department. The Executive Committee will consist of one representative from each participating academic unit, one of whom will be the program's Director, appointed by the Chairperson of the Mechanical Engineering Department. If the demands of the program grow, the Committee can increase in size maintaining equal participation from the partner academic units.

The members of the program's Executive Committee will be appointed to the Committee by the Chairperson of their associated academic unit. The Executive Committee will have authority over the approval of graduate electives that can contribute toward degree requirements, and revise, update, and maintain the list. The Committee will oversee admissions, core programmatic instruction including the integration of project and design activities, the approval of individual independent study courses for graduate credit toward the degree, and the organization of social events, seminars and workshops for the students and faculty involved in the program. Changes to the list of required courses for the program can be recommended by the Executive Committee and have to be subsequently approved by the Chairperson of Mechanical Engineering who is overseeing the program. The responsibilities of the program's Director include academic coordination, setting strategic directions and priorities, identification of opportunities, and advocacy for resources necessary for growth. All committee members, including the Director, will be appointed for three (3) years, with

the possibility of renewal. The position of the Director is expected to rotate between the members of the Executive Committee.

Administrative support for the program will be provided by the the Department of Mechanical Engineering in conjunction with the College of Engineering.

The program will be advertised and promoted online via a dedicated web page under the web site of the Department of Mechanical Engineering. The web page will make available publicly information about the affiliated faculty, the resources that are available and utilized by the program, news and events, as well as academic information such as the curriculum matrix and course sequence, the degree requirements, tuition information, and the list of approved graduate electives. The program's Executive Committee will have control over the content of the program's web pages, and be responsible for updating this content. A specific member of the Executive Committee will be appointed to oversee online content.

VII.A.2 Course requirements

The MSR program requires thirty (30) credit hours of graduate level coursework, and offer a Master Thesis or a course-based only track. Under the Master Thesis track, six (6) of the thirty (30) total credits must be Master's Thesis credits. Coursework must be completed with a grade point average of 3.0 or higher.

The program curriculum includes six (6) required courses (18 credits):

1. MEEG 621 Linear Systems
2. CISC 621 Algorithm Design and Analysis
3. MEEG 671 Introduction to Robotics
4. MEEG 667 Introduction to Autonomous Driving
5. CISC 642 Introduction to Computer Vision
6. MAST 632 Environmental Field Robotics

and four (4) out of a number of elective courses (expected to grow as the program expands) which in the basic program implementation are:

- MEEG 620 Intermediate Dynamics
- CISC 681 Artificial Intelligence
- MEEG 667 Introduction to State Estimation (Estimation I)
- MEEG 894 Linear Feedback Control Design (Multi-variable Control)
- CISC 684 Introduction to Machine Learning
- MEEG 667 Optimal Control I
- MEEG 867 Optimal State Estimation (Estimation II)
- MEEG 867 Decentralized Control & Game Theory
- MEEG 829 Applied Nonlinear Control
- MEEG 890 Nonlinear Programming

Along the Master-Thesis track, two (2) of the total four (4) electives are substituted for six (6) Master Thesis credits.

Students should take all six (6) of the required courses, and pick four (4) additional courses from the approved graduate elective list. Graduate-level independent study can substitute for up to six (6) graduate elective credits along a non-thesis degree track. Such substitutions need to have the written (hard copy or electronic) approval of the program's Executive Committee. Independent study activities can take place outside the campus, in the context of semester-long internships with approved industry or government partners (see Appendix D), but always under the supervision and oversight of a faculty member from the participating academic units, who will be ultimately responsible for assigning a grade for the course. The graduate student-industry partnership (GSIP) mechanism that will be set-up for the graduate students in mechanical engineering will be accessible to the students in the MSR program, who will thus be informed of available off-campus R&D project opportunities, provided by the industry and government partners who will subscribe. To facilitate academic assessment, all independent study courses receiving credit toward MSR degree requirements (including those available through GSIP) should lead to a tangible deliverable, including but not limited to a technical report, a research poster, or a prototype.

Through their choice of technical electives, students in the MSR program can shape their individual focus and academic concentration. Five specific concentration areas can be currently identified within the program, and each involving a set of three related fundamental courses. These concentrations will be optional to students in the MSR program, and for those who choose to follow them they can be added to their degree through the process of submitting a change of classification form:

1. *Control:*
   MEEG 621 (Linear Systems); MEEG 698 (Stochastic Optimal Control) or MEEG 894 (Linear Feedback Control Design); MEEG 829 (Applied Nonlinear Control)

2. *Estimation:*
   MEEG 621 (Linear Systems); MEEG 677 (Introduction to State Estimation); MEEG 877 (Sensing and Estimation in Robotics)

3. *Artificial Intelligence:*
   CISC 621 (Algorithms); CISC 684 (Machine Learning); CISC 642 (Computer Vision)

4. *Design:*
   MEEG 620 (Dynamics); MEEG 671 (Intro to Robotics); MAST 632 (Environmental Field Robotics)

5. *Optimization:*
   CISC 621 (Algorithms); MEEG 895 (Game Theory and Mechanism Design); MEEG 890 (Nonlinear Programming)

VII.B Assessment plan

Graduates of this program will be able to demonstrate different technical skills depending on their specialization through elective course selection. These skills may cover different aspects of design, analysis, simulation, and control of robotic systems. Yet all graduates should be able to demonstrate competency relative to the following three program learning outcomes:

1. Ability to derive mathematical models of typical robotic systems, analyze their dynamic behavior, and design standard controllers.

2. Ability to simulate robotic behavior in industry-standard software environments —e.g., ROS.

3. Familiarity with implementation issues related to deployment of robotic vehicles in real-world environments.

The first outcome can be assessed through required program courses MEEG 621 and MEEG 671, with additional data provided by elective courses MEEG 620, MEEG 694, MEEG 898, and MEEG 829. The second outcome will be demonstrated primarily in required courses MEEG 671, CISC 642, and MAST 632. The third outcome will be demonstrated in MEEG 678 and MAST 632. The latter course, MAST 632, is integrative and will require the combination of skills and knowledge acquired throughout the program.

APPENDIX

A Letters of approval from the College of Engineering

UNIVERSITY OF DELAWARE | College of Engineering
OFFICE OF THE DEAN

102 Du Pont Hall
Newark, DE 19716-3101
Phone: 302-831-2401
Fax: 302-831-8179

October 1, 2018

Ajay K. Prasad
Engineering Alumni Distinguished Professor and Chair
Department of Mechanical Engineering

Re: Master of Science in Robotics

Dear Prof. Prasad:

Thank you for providing the background and motivation to create a new Master of Science degree program in Robotics. I strongly believe that the proposed MS in Robotics program builds on our existing strengths across multiple departments and colleges at UD. I also believe that the establishment of this program can bring visibility to the University of Delaware, and enhance our reputation and leadership in a critically important field. Therefore, I am very supportive of your proposal.

I wish you the best of luck in this important initiative.

Sincerely,

Levi T. Thompson
Dean, and
Elizabeth Inez Kelley Professor of Chemical Engineering

Cc: Michael E. Matthews

UNIVERSITY OF DELAWARE | College of Engineering
OFFICE OF THE DEAN

University of Delaware
102 du Pont Hall
Newark, DE 19716-3101
Phone: 302.831.2401
Fax: 302.831.8179

September 27, 2018

Ajay K. Prasad
Engineering Alumni Distinguished Professor and Chair
Department of Mechanical Engineering

Re: Master of Science in Robotics

Dear Prof. Prasad:

I am pleased to write in strong support of the proposed Master of Science degree program in Robotics. This is the kind of innovative program that can provide the University of Delaware and the College of Engineering a platform for great visibility and leadership in a critical field of endeavor, with significant implications for technological and societal impact at the national and international levels.

I wish you the best of luck in this important initiative.

Sincerely,

Babatunde A. Ogunnaike
Dean, and
William L. Friend Chaired Professor of Chemical Engineering

Cc: Michael E. Matthews

B Letters of approval from contributing Departments

UNIVERSITY OF DELAWARE | College of Engineering
DEPARTMENT OF COMPUTER & INFORMATION SCIENCES

101 Smith Hall
Newark, DE 19716
Phone: 302.831.2711
Fax: 302.831.8458
Email: krystalp@udel.edu

October 1, 2018

Ajay K. Prasad
Engineering Alumni Distinguished Professor and Chair
Department of Mechanical Engineering

Re: Master of Science in Robotics

Dear Prof. Prasad:

The Department of Computer and Information Sciences strongly supports the proposed Master of Science degree program in Robotics. The proposed MS in Robotics builds on existing department, college and university efforts in this area and establishes UD leadership in this critical discipline.

The Department of Computer and Information Sciences is happy to support the inclusion of the following departmental courses within the program:

CISC 621 (Algorithm Design and Analysis)
CISC 642 (Introduction to Computer Vision)
CISC 681 (Artificial Intelligence)
CISC 684 (Introduction to Machine Learning)

We in CIS look forward to supporting the Department of Mechanical Engineering in building this exciting new MS program.

Sincerely,

Kathleen F. McCoy
Chair
Department of Computer and Information Sciences

UNIVERSITY OF DELAWARE | College of Earth, Ocean, & Environment
SCHOOL OF MARINE SCIENCE & POLICY

Hugh R. Sharp Campus
700 Pilottown Road
Lewes, DE 19958-1298 U.S.A.

October 1, 2018

Ajay K. Prasad
Engineering Alumni Distinguished Professor and Chair
Department of Mechanical Engineering

Re: Master of Science in Robotics

Dear Prof. Prasad:

The School of Marine Science and Policy is pleased to support the proposed Master of Science degree program in Robotics. The proposed MS in Robotics builds on existing department, college and university efforts in this area and will help to cement UD's leadership in this critical discipline.

The School of Marine Science and Policy supports the inclusion of the following course within the program:

MAST632 (Environmental Field Robotics)

I expect that the inclusion of this course will help to distinguish UD's MS in Robotics program from our competitors and make it more attractive for applicants.

We in SMSP look forward to supporting the Department of Mechanical Engineering in building this exciting new MS program.

Sincerely,

Mark A. Moline
Director, School of Marine Science and Policy

C Letters of collaborative agreement

UNIVERSITY OF DELAWARE | College of Earth, Ocean, & Environment

Arthur C. Trembanis
Associate Professor of Oceanography
Director UD Maker Gym
103B Robinson Hall
Newark, DE 19716 U.S.A.
Phone: 302-831-2498
Fax: 302-831-4158
Email: art@udel.edu

October 4, 2018

Ajay K. Prasad
Engineering Alumni Distinguished Professor and Chair
Department of Mechanical Engineering

Re: Master of Science in Robotics

Dear Prof. Prasad:

I am pleased to express my strong support of the proposed Master of Science degree program in Robotics. As an instructor of one of the courses included in the program's curriculum plan, and Faculty Director of UD's Maker Gym, I am happy to be involved in the effort, and make the Maker Gym resources available to, and integrated in, the new MS in Robotics program. I believe there will be valuable and exciting synergy between the resources of the Maker Gym and this new Robotics MS degree program. The Maker Gym is well located on central campus as a hub for students in this new program to conduct collaborative design and fabrication with meeting spaces, wood shop, electronics and additive manufacturing and digital technologies to support ideas from concept to prototype.

I look forward to welcoming students and faculty involved with the MS Robotics cohort to the Maker Gym.

Sincerely,

Art Trembanis, Ph.D.
Director UD Maker Gym
Associate Professor Oceanography

Cc: Mohsen Badiey, Dan Freeman, Mark Moline

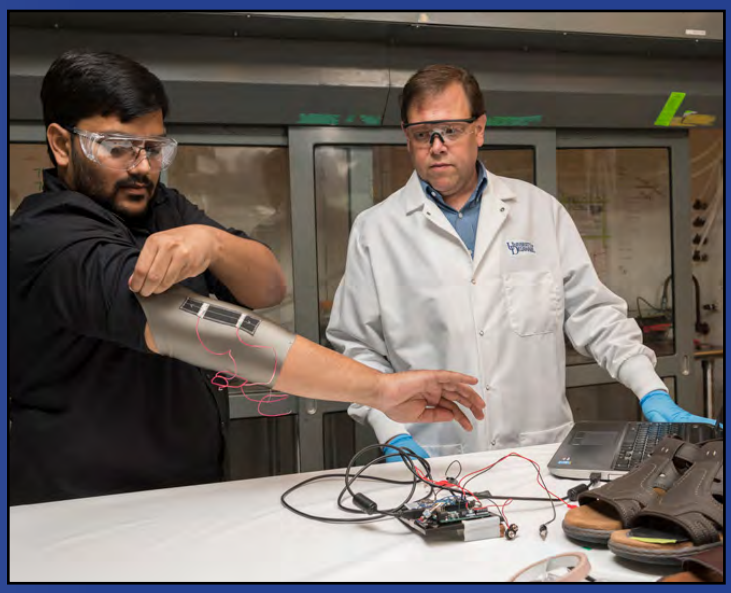
D Graduate Student-Industry Partnership Flyer

University of Delaware Mechanical Engineering
Graduate Student – Industry Partnerships

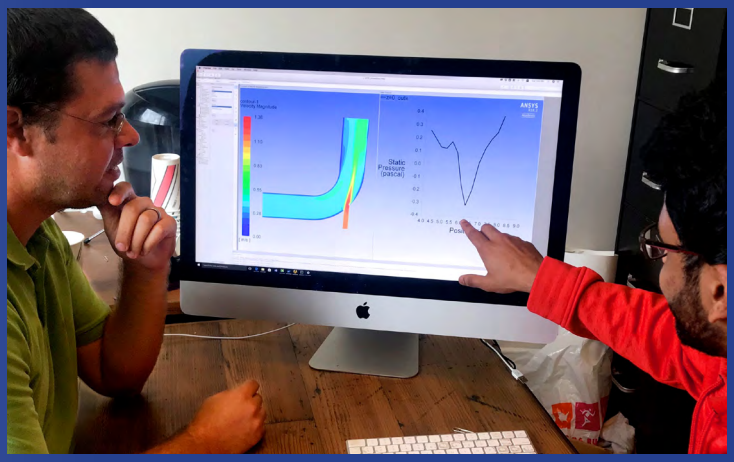
Does your business have a need for engineering analysis, materials characterization, or testing? Is your business interested in connecting with students from the region's premier research institution? If so, this new Graduate Student-Industry Partnership will be of interest.

Starting Spring 2019, the University of Delaware Department of Mechanical Engineering would like to offer industry-focused research and development experiences to our graduate students.

Graduate students enrolled in the program will receive university credits for participating in industry-led research and development projects.



Students will benefit by gaining industrial research experience while connecting with potential employers. Businesses will benefit by engaging highly trained graduate students to solve technical problems while identifying potential employees.



Advantages over traditional internship

- No salary support required
- No sponsorship fees*
- No visa paperwork for foreign students
- Access to most university equipment and resources.
- Advising assistance from a UD Mechanical Engineering faculty member
- Flexible work scope (150 - 300 hrs/semester)

** Sponsor provides material and protyping costs as needed*

To Participate

To learn more about this opportunity please contact department chair Dr. Ajay Prasad (prasad@udel.edu). If you are ready to participate please fill out the online form: https:// form.jotform.com/82468605729165. We will use the project information you provide to aid in student-sponsor alignment. Opportunities begin February 2019 and continue each semester.

E Library assessment

UNIVERSITY OF DELAWARE | University of Delaware Library
VICE PROVOST FOR LIBRARIES AND MUSEUMS
AND MAY MORRIS UNIVERSITY LIBRARIAN

181 South College Avenue
Newark, DE 19717-5267
Phone: 302-831-2231
Fax: 302-831-1046

October 12, 2018

Memorandum

To: Herbert G. Tanner
Professor and Graduate Curriculum Director
Department of Mechanical Engineering

From: Trevor A. Dawes
Vice Provost for Libraries and Museums
and May Morris University Librarian

I am responding to your request to supply information about the capability of the University of Delaware Library, Museums and Press to support the proposed Master of Science in Robotics.

The existing online and print collections of the University of Delaware Library, Museums and Press, which are strong in the sciences and related interdisciplinary areas, are currently able to support this program. However, no additional funding is available for new resources. Enclosed is a description of collections, resources and services available for this purpose.

I would be pleased to respond to any questions.

/nb
Enclosure

c: Department of Mechanical Engineering
Tsu-Wei Chou, Unidel Pierre S. du Pont Chair

University of Delaware Library, Museums and Press
Susan Davi, Associate Librarian and Head, Collection Management and Licensed Electronic Content Department
M. Dina Giambi, Associate University Librarian for Budget and Collections
Thomas Melvin, Librarian, Reference and Instructional Services Department
Sandra Millard, Deputy University Librarian and Associate University Librarian for Public Services and Outreach
Carol Rudisell, Librarian and Head, Reference and Instructional Services Department
William Simpson, Associate Librarian and Institutional Repository Librarian, Reference and Instructional Services Department

Faculty Senate
Karren Helsel-Spry, Administrative Assistant IV

University of Delaware Library
VICE PROVOST FOR LIBRARIES AND MUSEUMS
AND MAY MORRIS UNIVERSITY LIBRARIAN

181 South College Avenue
Newark, DE 19717-5267
Phone: 302-831-2231
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October 12, 2018

Report on Library Services and Collections in Support of the Master of Science in Robotics

General Description

The University of Delaware Library, Museums and Press includes the Hugh M. Morris Library, where the main collection is housed; two branch libraries located on the Newark campus, the Chemistry Library and the Physics Library; and a third branch library, the Marine Studies Library, located in Lewes, Delaware. The Library collections parallel the University's academic interests and support all disciplines.

Databases, full-text electronic journals and electronic books, books, periodicals, microforms, government publications, maps, manuscripts and media provide a major academic resource for the University of Delaware, the surrounding community, the state of Delaware and the nation. Library staff members provide a wide range of services.

The University of Delaware Library, Museums and Press is a U.S. depository library and a U.S. patent depository library and contains the complete file of every patent issued by the U.S. Patent and Trademark Office (USPTO).

The online catalog, DELCAT Discovery, provides access to millions of items by author, title, subject and keyword.

Library collections number over 2,720,000 and are broadly based and comprehensive. In 2016/2017, the Library Web <library.udel.edu/> received over 3,900,000 page views.

Specific Support for Robotics

The Library's collections are strong and are able to support the proposed Master of Science in Robotics. For many years, the Library has supported related graduate and undergraduate programs in all areas in engineering, computer science, materials science, environmental sciences, and physics. The collections in these areas are excellent and continue to grow.

An experienced librarian, Tom Melvin (tmel@udel.edu), Librarian, Reference and Instructional Services Department, serves as the Library liaison to the faculty in the Department of

Mechanical Engineering. As Library liaison, Mr. Melvin works with the Department of Mechanical Engineering to:

- Further develop Library collections, both print and electronic to support the teaching, learning and research needs of the Department's programs
- Provide research support for faculty and students in a consultation setting
- Provide instruction in a classroom setting
- Serve as a resource for the information needs of the faculty and students as they relate to the Library, Scholarly Communication, Open Access and other topics

Another science librarian has considerable expertise in related subject areas and can provide additional specialized services, as needed:

- William Simpson (wsimpson@udel.edu) – Computer & Information Sciences, Physics, Mathematical Sciences

More than 200 research guides <guides.lib.udel.edu/> in all subject areas have been developed and are maintained by librarian liaisons. These research guides describe library resources and assist students in the research process. These guides introduce students to a wide array of useful resources including databases, eJournals, eBooks, reference materials, visual material and more. The librarians mentioned above are also available to work with faculty to develop research guides for specific courses within this program.

The Library subscribes to more than 400 online databases <library.udel.edu/databases/> which support research in all areas. Among the most important databases for study and research in robotics are: *Compendex/Engineering Village*, *Scopus*, *Web of Science*, *Materials Science & Engineering Database*, *ACM Digital Library*, *Springer Materials*, *ASTM Standards & Engineering Digital Library, and SPIE Digital Library.*

In addition to its extensive print-based collections, the Library provides access to more than 100,000 electronic journals <library.udel.edu/ejournals/> and more than 670,000 electronic books <library.udel.edu/ebooks/>. Within the Library's eJournal collection, the sciences are particularly strong, including almost all the journals published by Elsevier, Springer, Wiley, and Taylor & Francis, as well as smaller publishers such as ACM, ASME, Nature, IEEE and IET, Annual Reviews, and SPIE.

Within the eBook collection, online access to almost all ebooks published by Springer from 2005-present are of particular importance. *Knovel* and *Safari Tech Books* provide sci-tech reference data and ebooks on technology topics. The conference proceedings from major publishers such as ACM, IEEE, SPIE, and Springer are also available online. A number of important book series published by Springer (e.g., *Lecture notes in computer science*, *Lecture*

notes in control and information sciences, *Tracts in Advanced Robotics*, *Springer Proceedings in Advanced Robotics*) are available online.

The Library subscribes to *RefWorks*, a web-based citation management tool that can be used with most databases. Access to *EndNote Online* via the Library's *Web of Science* subscription is also available.

The Library has strong collections of film and video <library.udel.edu/filmandvideo/> which support study and teaching in all subject areas.

The Library has a nationally recognized Student Multimedia Design Center <library.udel.edu/multimedia/> which provides access to equipment, software, and training related to the creation of multimedia projects. The Student Multimedia Design Center includes over 80 workstations, six studios, and two classrooms focused on multimedia creation. University of Delaware users also may borrow a wide variety of multimedia equipment. Through its Multimedia Literacy program, the Student Multimedia Design Center provides instructional support for faculty seeking to incorporate multimedia into their assignments.

The Library also maintains an Institutional Repository (<udspace.udel.edu/>), which archives research reports, documents, and other resources produced by University of Delaware faculty and students.

Trevor A. Dawes
Vice Provost for Libraries and Museums
and May Morris University Librarian