CSME BULLETIN SCGM
THE CANADIAN SOCIETY FOR MECHANICAL ENGINEERING
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Non-electric Applications of Nuclear Energy

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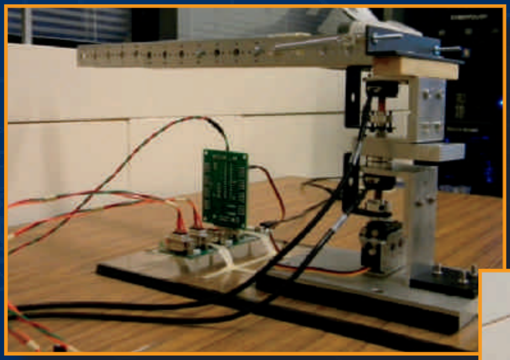

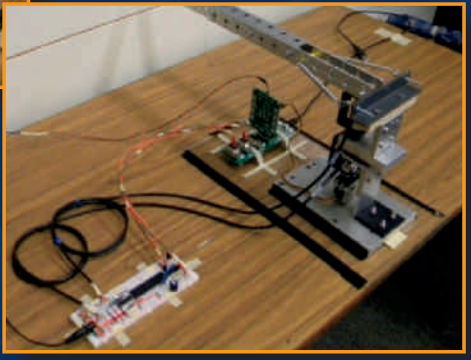

Control of Space Robotic Manipulators with Joint Flexibility

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President's Message/Message de la Présidente

Christine Wu, Ph.D., P.Eng., FCSME

President's Message

It has been one year since I became CSME President, and I would like to share with all of you a few thoughts. CSME had another good year - a year of enthusiasm and growth. We had our CSME 2013 Honours, Awards and Fellowships Ceremony in June during CANCAM 2013, which was held on the beautiful campus of University of Saskatchewan. Five well-deserved CSME members at various stages of their careers shared three medals and two awards. We also inducted five new CSME Fellows. It is truly inspiring to see our members' achievements and it is truly an event of celebration.

We have always given high priority to support our student members. We launched a new student activity support program in January, 2013, which provides support to student chapters to organize various activities for professional development. The new CSME website provides updates on such activities. So far, seven events have been supported by CSME Student Affairs, and the students' responses have been extremely positive. More initiatives are being prepared. We are excited to see more students engage with CSME.

Expanding CSME membership base and to bring members from industries and academic institutions together on a common platform has always been the focus for CSME. We have developed a plan to improve our service and visibility, including major revisions to the CSME website and the on-line membership payment system. I am delighted to report that our membership revenue has increased by 30% for the first six months of 2013 as compared to the revenue of entire year of 2012.

To expand, we need to stay relevant and we need to collaborate with other partners to extend our functionality and effectiveness. For the first time, CSME is working with CFD Society of Canada to have the 22nd CFD Annual Conference as a concurrent conference with the CSME International Congress 2014, which will be held at University of Toronto from June 1-4, 2014. I would like to encourage all of you to attend and to network with the fellow engineers. I have no doubt that it will be an exciting event.

Looking forward, I am absolutely optimistic that a more exciting year is ahead of CSME.

Christine Q. Wu, Ph.D., P.Eng., FCSME
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Ça fait déjà un an depuis le début de mon mandat comme présidente de la SCGM, et je voudrais partager avec vous mes réflexions. La SCGM a connu une autre bonne année - une année d'enthousiasme et de croissance. En juin, nous avons eu la cérémonie de remise des prix et distinctions de la SCGM lors du congrès CANCAM 2013, qui s'est tenue sur le magnifique campus de l'Université de la Saskatchewan. Cinq membres de la SCGM, qui sont à différents stades de leurs carrière, ont méritées trois médailles et de deux prix. Nous avons aussi élus au rang de « Fellow » cinq nouveaux membres de la SCGM. Cette célébration est l'occasion de voir les réalisations de nos membres et c'est vraiment inspirant.

Nous avons toujours donné priorité à soutenir nos membres étudiants. Depuis janvier 2013, nous avons lancé un programme de soutien aux étudiants qui offre aux chapitres étudiants des fonds afin d'organiser diverses activités de développement professionnel. Le nouveau site de la SCGM contient la liste de ces activités. Jusqu'à présent, sept évènements ont été soutenus par la SCGM et les commentaires des étudiants ont été extrêmement positifs. Présentement, plusieurs initiatives sont en cours d'élaboration. Nous sommes heureux de voir que davantage d'étudiants s'associent avec le SCGM.

La SCGM est constamment désireuse d'élargir le nombre de ces membres. Elle cherche à accroitre le nombre des membres provenant de l'industrie aussi bien que des institutions académiques afin d'offrir une plateforme commune de discussion. Nous avons donc développé un plan visant à améliorer nos services et notre visibilité, y compris des mises à jour majeures du site de la SCGM et aussi l'ajout le système de paiement des membres en ligne. Je suis très heureux d'annoncer que nos recettes lies aux membres ont augmenté de 30 % lors des six premiers mois de 2013 par rapport au revenu de l'ensemble de l'année 2012.

Pour nous développer, nous devrons rester pertinents, nous devons collaborer avec d'autres partenaires pour étendre nos actions et notre activité. Pour la première fois, la SCGM travaille avec Société Canadienne de CFD afin offrir la 22ème Conférence annuelle de la CFD en commun avec le congrès 2014 de la SCGM, qui aura lieu à l'Université de Toronto du 1 au 4 juin 2014. Je ne doute pas que ce sera un événement conjoint excitant qui offrira un forum de discussion et de réseautage avec les collègues ingénieurs.

En se tournant vers l'avenir, je suis optimiste que des années excitantes sont à prévoir pour la SCGM.

Christine Q. Wu, CSME Président

CSME Advertising

Contributing to the CSME Bulletin

We welcome submissions of events, announcements, job postings, and feature articles relevant to mechanical engineering from researchers and engineers in Canada. Feature articles in forms of both review and research papers are welcome. The articles should be technical, general, and no more than 6000 words. If you are interested in submitting an article to the Bulletin, please contact the Editor at xiaodong.wang@ualberta.ca.

Contributing to the CSME Bulletin

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Student Affairs: Exciting Opportunities to Engage with CSME

by Sushanta K. Mitra, P.Eng., FASME, FCSME
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Students are the critical component of any professional organization. CSME values the student engagement and hence has revived its strategy towards involving the local student chapters in shaping the future of the mechanical engineering students within different post-secondary institutes of this country. The new CSME website provides, in regular basis, updates on different activities conducted at the local chapters across the country. CSME has launched a new student activity support program this January, which provides support to individual chapters to host invited talks, popular lectures, and industrial tours for the students. This newly formed program is supported through a modest seed fund of $500 annually given to each chapter to cover all such professional activities within a calendar year. The coordinator of the student chapter is required to fill-out a short form about the proposed activity with an estimated budget for approval from CSME. The approved activities are then showcased in CSME website and the coordinators are also required to submit a post-activity short report. So far, seven such events were supported by CSME Student Affairs. The response has been very encouraging. This is also helping us to grow the grass-root base for CSME and renewed interest among students in engaging with one of the premier professional organizations of this country. Some more initiatives are in pipeline. Stay tuned!

Student activities

Beat Paper award in TCSME

The 2012 Beat Paper award in the Transactions of CSME

by Matthew John D. Hayes, Ph.D., P.Eng.
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The 2012 Beat Paper award in the Transactions of the Canadian Society for Mechanical Engineering was awarded to Ridhan Hannat, Francois Morency, Louis Decaster for their paper "Numerical study of an aircraft hot air anti-icing system", Vol 37, No 1, 2013. It was presented at the 2013 Committee for the Theory of Machines and Mechanisms (CCToMM) Mechanisms, Machines, and Mechatronics Symposium at École de technologie supérieure in Montreal, May 30-31, 2013. The award was presented to Francois Morency and Louis Decaster by Ilian Bonev, Managing Editor of the TCSME.

Non-electric Applications of Nuclear Energy

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Nuclear energy is often thought of and treated as inextricably linked to electricity generation. That is because nuclear energy today is basically an electricity-generation technology. But the prospects for nuclear energy are significantly broader, as I learned as a participant in a joint expert workshop entitled, "Technical and Economic Assessment of Non-electric Applications of Nuclear Energy," held April 4-5 of this year in Paris (http://www.oecd-nea.org/ndd/workshops/nucogen/). The workshop was co-organized by the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) and the International Atomic Energy Agency (IAEA), and was attended by thirty individuals from nine countries (Canada, Finland, France, Germany, Korea, the Netherlands, Poland, Switzerland, the U.S.), including representatives of engineering companies and industry, universities and research institutions, and international organizations.

The objectives of the workshop included identifying the technological and economic challenges facing non-electric applications of nuclear energy, and assessing the potential of non-electric applications of nuclear energy to provide advantageous contributions to future energy needs.

Recent Developments in Energy Systems

Global and national energy systems have undergone numerous developments in the previous decade, especially in the last few years, that affect nuclear energy. Some of these follow:

- The use of fossil fuels and related greenhouse gas emissions have increased for energy-related uses in many countries, due to abundant supplies of fossil fuels like coal and gas and decreases in prices of natural gas, as well as difficulties in attaining and international agreements on reducing greenhouse gas emissions.
- The role of base-load electricity generation technologies like nuclear are changing as the use of renewable energy technologies expands, especially intermittent ones like wind and solar.
- Due to the global economic crisis, energy consumption has declined in most countries in recent years and funding for energy projects has become scarcer.
- The Fukushima Daiichi accident affected public acceptance of nuclear technology by increasing concerns in the public over the safety of nuclear energy.

Nuclear Energy Today

Today, nuclear power plants produce electricity that is competitive with other technologies, with little or no carbon outputs, thereby avoiding exacerbating the challenges associated with climate change. Many countries operate nuclear power plants, including Canada (see Figure 1). Nuclear reactors are usually operated to provide base-load electricity with a high availability, although nuclear reactors are operated in a few countries in a load-following mode, in order to provide the ability to cope with rapid changes in demand and/or intermittent production from other sources.

Non-electric Energy Applications of Nuclear Energy

Non-electric applications of nuclear energy range from the provision of heat (at temperatures ranging from low to high), cogeneration (or combined heat and power), desalination, production of hydrogen and other chemical fuels, synergistic applications with renewable energy sources, and energy storage via coupling of nuclear and intermittent renewable energy sources. Some applications of nuclear energy for non-electric uses have been understood for decades and, in cases like desalination and district heating, been demonstrated or implemented industrially. But such applications have been quite limited.

Details on some of the non-electric applications of nuclear energy described in the workshop follow:

- **District heating**: Experiences in operating nuclear district heating, or planning for such applications, were described for several countries. The presentations covered experiences from operating nuclear district heating in Switzerland and Russia (all in a cogeneration mode), a feasibility study of developing district heating for an existing nuclear power plant in France, and a description of a nuclear district heating project proposal in Finland. The latter, which involved a presentation of a plan for nuclear district heating from the Loviisa nuclear plant for the metropolitan area of Helsinki, was of particular interest to me, as it was deliverd by Fortum, a company for which I worked (under its previous name of Imatra Voima Oy) during an engineering student placement in Helsinki.
- **Desalination**: Experiences in nuclear desalination were described, including the development of the Korean SMART reactor for desalination markets and the experience of operating a fast breeder reactor in Kazakhstan for electricity and fresh water production. The IAEA's work on nuclear desalination as well as the work of the OECD Environment Directorate in the area of water resources, were also described.
- **High-temperature process heating**: A historic overview of high temperature heating applications was presented, and numerous process heating applications provided by high temperature gas-cooled reactors (HTGRs) were described. Overviews were provided of the process heat applications and associated economic aspects considered in the Next Generation Nuclear Plant (NGNP) project in the United States, and of European Union markets for process heat applications. Business models for industrial process heat applications were also described based on the NGNP project.

- **Cogeneration**: A study performed by the European Joint Research Centre on cogeneration markets in the European Union was described. Also, discussed was the competitiveness of nuclear cogeneration in a future energy system and integration challenges for nuclear cogeneration. The application of exergy-based methods for nuclear cogeneration, as well as relevant economic models and methods, were presented. A history was given of nuclear cogeneration applications to provide context, and it was pointed out that nuclear cogeneration has record of over 750 reactor-years of experience in non-electric applications (mainly for district heating and desalination).
- **Synergistic applications of nuclear energy with renewable energy sources**: Energy systems can synergistically integrate nuclear energy plants with variable renewable technologies, to increase penetration levels of renewable energy. Such integration can help mitigate some of the intermittency challenges of renewable energy sources and the need for energy storage for renewables. A recent study by the NEA was discussed future low carbon electricity systems, including nuclear and renewable energy technologies. Also, the potential role that nuclear energy could play by the middle of the next decade in France was described, where the share of nuclear power would be reduced from 75% to 50%.
- **Hydrogen and alternative fuel production**: The prospects for nuclear hydrogen production were discussed, including the outcome of a cost comparison between various advanced processes hydrogen production coupled to nuclear reactors.

Non-energy Nuclear Applications

Non-electric uses of nuclear reactors also include non-energy applications, some of which have been known and/or utilized for several decades. But these were not included in the workshop scope, which focused on energy applications. Nonetheless, it is pointed out here for completeness that non-energy applications include, according to the World Nuclear Association (http://www.world-nuclear.org/info/Non-Power-Nuclear-Applications/Overview/The-Many-Uses-of-Nuclear-Technology/), the production of radioisotopes and radiation for numerous applications:

- **Industry**: Nuclear materials and techniques have been applied to a range of industrial needs, including environmental tracers, detecting and analysing pollutants, industrial tracers, instrumentation and radiography.
- **Household**: One of the most common uses of radioisotopes today is in household smoke detectors.
- **Agriculture and food**: Nuclear uses are aimed at improving the sustainability of these activities, as well as better management of fertilizer application, increasing genetic variability, insect control, food preservation, and management and conservation of existing water supplies and the identification of new ones.
- **Medicine**: Uses range from diagnosis to therapy, and include equipment sterilization.
- **Research**: Various research applications of nuclear energy exist, including the use of radioisotopes dating (i.e., determining the age of substances).

Challenges and Needs

The challenges, now and in the future, associated with developing and implementing non-electric applications of nuclear energy are numerous. The further development of such applications will require technological challenges to be overcome. For instance, it is important to provide sufficient flexibility to permit switching between electricity generation and non-electric applications, depending on electricity prices. This is likely to be true whether dealing with current nuclear reactor technology or advanced designs that operate at higher temperatures. Also, the further development of non-electric applications of nuclear energy will require sound business cases, demonstrating that such applications are competitive with fossil-fuel based or other technologies that can be used for the same applications. For example, some of the economics-related needs to foster non-electric applications of nuclear energy, include the following:

- Development of suitable economic approaches and models to assess the costs of non-electric applications of nuclear energy.
- Reducing the uncertainties in reactor technology cost assessments, as these significantly and affect directly the competitiveness of the non-electric nuclear applications.
- Demonstration of the competitiveness of non-energy applications of nuclear energy.
- Development of an enhanced understanding of energy markets relevant to non-energy applications of nuclear energy.

Finally, it is also important to increase and improve communications about the merits of non-electric applications of nuclear energy among the numerous stakeholders (e.g., network operators, heat generators, users, municipalities) in such applications.

Closure

The potential uses of nuclear energy extend beyond the realm of electricity supply today and, based on information and views presented at the workshop, are likely to do so increasingly in the future.

Figure 1. The Darlington Nuclear Generating Station, located in Durham Region about 70 km east of Toronto. This four-unit electrical generating station has a total output of 3512 MW and provides about 20% of Ontario's electricity needs. [Copyright © 2013 Ontario Power Generation Inc., all rights reserved. This information is subject to the general terms of use set out in Ontario Power Generation Inc.'s web site (www.opg.com).]

Concordia Institute of Aerospace Design and Innovation (CIADI)

Nadia Bhuiyan
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The Concordia Institute of Aerospace Design and Innovation (CIADI) was founded in 2001, and was conceived to promote awareness and provide leading edge know-how among engineering students engaged in aerospace design and innovation. In addition to the undergraduate internship program, CIADI has evolved and now also promotes aeronautics and space research collaboration through a coordinated research organization. The objectives of CIADI are to train highly qualified personnel relevant to the needs of the aerospace industry and its supply chain companies and to facilitate research collaboration between aerospace related faculty, the aerospace industry, government agencies and other aerospace related institutions.

In terms of the internship program, the Institute conducts collaborative industry-driven design and research projects of 500 to 1000 hours per year, which can be undertaken in the summer, fall and/or winter. CIADI students are selected from among the top undergraduate students in the Faculty of Engineering and Computer Science and are supervised by aerospace industry engineers as well as Concordia professors. CIADI also offers students the opportunity to work on internships abroad, known as the CIADI Global program. The Institute also offers students the opportunity to work on research projects within the university with professors, and this works well for those who have an interest in continuing graduate studies in the field of aerospace. The institute offers an excellent learning opportunity for undergraduate and graduate students in the M.Eng. Aerospace program to familiarize themselves with the aerospace industry through organized visits, tours, to aerospace companies special training courses, conferences and social events related to aerospace. CIADI not only provides excellent exposure to the aerospace industry, but also helps graduating students find employment, as well as industry to find well-qualified recruits.

From its inception, CIADI, as an internship program, has been funded by the aerospace industry and by other funding organizations over the past 11 years. Some of these partners are Pratt & Whitney Canada, Bombardier Aerospace, Bell Helicopter Textron, and Rolls-Royce Canada, among many others. In the Global program, the Institute has sent students to: Poland (PWK, Poland, WSK, Poland); Italy (DEMA, Piaggio Aero Industries, CIRA); France (Onera, Airbus France); Germany (MTU Aero Engines, Lufthansa Technik AG, Technische Universität München); Belgium (Université Libre de Bruxelles); Spain (Airbus Military); Portugal (Airforce Academy); Israel (Technion Israel Institute of Technology); USA (NASA, Hawker Pacific, University of Pennsylvania, University of Boulder); and Singapore (National University of Singapore).

In order to address industry needs, focused training is provided through short courses such as ACCESS, MATLAB, CATIA and others. CIADI and its students are actively involved in various aerospace conferences, forums and students' competitions. CIADI students work on real, well-defined industry projects. A one-day start-up training is offered to all students, where short courses on the aerospace industry at large are offered by industry professionals to give a broad initiation to the industry.

The Institute conducts monthly progress meetings that expose students to a variety of research projects. A number of CIADI projects are normally credited by the faculty as Capstone design projects. Through preliminary industry research projects, the institute provides "an initiation to research" for students who intend to pursue graduate studies in aerospace. This program is part of the Consortium de recherché et d'innovation en aérospatiale au Québec (CRIAQ).

CIADI also has a student President, Vice-President, and a number of Executives that help organize events, attend conferences on behalf of CIADI, and generally act as ambassadors of the Institute. CIADI also holds networking events for the alumni and industry on a yearly basis.

In the decade since CIADI's inception, hundreds of students have passed through the institute and found their place in the aerospace industry. What CIADI has done for our students is beyond what we could have imagined. Undergraduate students taking on supervisory roles, graduates finding themselves landing their first job managing large groups of employees, and best of all, rather than having the problem of finding a job, having the lesser problem of deciding which offer to accept. Today, it is our alumni who have come full circle and are hiring CIADI students, so they are paying it forward in a sense.

I have served as Associate Director at CIADI for 11 years, and I am always impressed with the calibre of our students. After completing an internship, they get a look of excitement and hope for what the future holds for them and you can just feel that they will go places they couldn't have imagined before being a part of CIADI.

Concordia Institute of Aerospace Design and Innovation (CIADI)

Concordia was the pioneer of this industry-university collaboration model, and today, we work together with three Montreal universities, École Polytechnique, ÉTS, McGill University, to form the Montreal Aerospace Institutes (MAI), to produce the best graduates for the aerospace industry. We expect to build more momentum in the coming years. CIADI is shaping the next generation of the aerospace industry. Our students truly are the future of aerospace in Montreal.

CIADI People and Places

Some of our local partners.

Some of our global partners.

THE IMPACT OF IMPACT

G.S.H. Lock FCSME

Ever since we could throw rocks, humans have been critically aware of the effect that a sudden impact can have on the body. Being the first to throw undoubtedly assumed a much higher priority than the development of an ability to dodge the projectile, but sooner or later we would come to know the injury first hand. The club, the sword and the arrow only made things worse. And it is hardly necessary to add that guns, mines and bombs have not contributed much to modern civility.

Today we find ourselves facing the same traumatic effects as ancient man. Science and technology have made them worse, but medical science in particular has helped alleviate distress and, to some extent, compensate for functional loss. In peace and in war, bruises and cuts have been healed, broken bones restored and artificial limbs installed. We are fortunate that much of today's medicine is dedicated to restoration and recovery; sadly, we concentrate more on effects than causes.

On the battlefield, the intention to inflict impact injury is deliberate and expected. In peace-time, and especially during the hours when each of us goes about his or her daily life, we expect to avoid impact injury. That it may occur is well known to the automobile industry and, regretfully, in the world of professional sport. Much has been written on the attendant damages of impact but there is still an outstanding need to develop strategies, schemes and devices which can help alleviate damage if not prevent it entirely.

It seems almost obvious to point out that impact injury is caused by the force of impact being absorbed in the destruction of bone and tissue, but it is equally obvious that we cannot conduct human experiments to uncover the details. We are left with the results and the informed speculation of the surgeon on how the force has compromised integrity and how the damage can be repaired. No doubt the magnitude of the force itself will be a matter of speculation.

Perhaps it would be better to couch the discussion in terms of thermodynamics rather than mechanics; that is, to speak of the energy of impact and the energy of its absorption. The First Law makes it clear that they are equal and the Second Law holds the promise of dissipation. The force during a collision, for example, may not be known, but the energy of the colliding body can be estimated from its mass and velocity. Whether or not this approach would help the medical scientist I cannot say but it might guide their experiments. Animal tissue, for example, could be tested under a range of impact energies to determine its ability to absorb and dissipate the energy in what has become known as blunt trauma.

A similar strategy could be applied to protection devices. As a pad or lining, they could be subjected systematically to a progression of impact energies, and measurements made of their ability to absorb them. Clearly, their dissipative ability would become paramount. Two parallel magnetic plates, for example, could generate an electric current if squeezed together. The Joulean loss in a resistive wire would dissipate energy.

Similarly, the spring-dashpot mechanism might be useful. It is well known that a door so-fitted will dissipate the energy stored in the spring when the door is left to close by itself.

The mechanical engineer has considerable knowledge of energy, its forms, its transformation and its degradation. Not surprisingly, the profession has been active in developing and promoting a variety of causes of impact over many millennia. But it is only recently that we have undertaken the task of mitigating its effects. Leaving aside the obvious benefit of armour plating to ancient warriors, it is fair to say that the modern automobile industry has led the way and paid considerable attention to the impact injuries to which passengers may be subjected. And it would be cynical to suggest that their motivation was simply to use safety as a means of boosting sales. Much has been learned from pioneer collision experiments which have led not only to the reduction of injury but to a restriction of their causes.

In general, there is an outstanding need to study both the causes and the effects of impact on the human body. Military applications abound, especially now that terrorism has assumed such a prominent place in our society, but even in day-to-day civilian life the need is much greater than is generally recognized. In sport, for example, the need to protect the foot, the shin, the knee, the elbow, the shoulder and, above all, the head and neck, deserves much greater attention than it currently receives. In all of these, the problem is the same: how to estimate the energy of impact and how to construct a covering device which, in dissipating energy, can reduce the impact force to an acceptable level.

In recent years, Dr Tom Nelson, Distinguished University Professor Emeritus at the University of Alberta had a hip-protecting device built and tested. The data revealed that the force of impact (accelometrically measured) could be reduced by 20 – 70%. The concept is now being studied in the Department of Mechanical Engineering in an investigation into helmet safety conducted by Dr Chris Dennison as part of his ongoing research on helmets. Given the impact on society of impact studies such as these, the Canadian Society for Mechanical Engineering might well consider sponsoring an annual conference or the formation of a separate division of specialization dedicated to activities of such a high order.

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Control of Space Robotic Manipulators with Joint Flexibility

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Abstract

This paper firstly provides a brief review of current activities of robotic manipulators in space on-orbit serving and the development of control theory for robotic manipulators to capture a non-cooperative target. Then, a hybrid input shaping-based impedance controller has been proposed to suppress the residual vibration of the robotic manipulator resulting from the flexibility of manipulator joints. The proposed controller consists of two parts: an open-loop input shaping and a close-loop impedance control. Numerical simulation and experimentation have also been conducted to validate the proposed control scheme.

Nomenclature

A_i	= Amplitude of the *i*th impulse
b	= Damping factor of the impedance function
EI	= Extra-Insensitive
J	= Rotational inertia of the link
J_m	= Rotational inertia of the motor
K	= Stiffness of the flexible joint
k	= Stiffness factor of the impedance function
m	= Inertia factor of the impedance function
P	= Impulse sequence of EI shaper
PRV	= Function of percentage residual vibration
q	= Link angle
q_d	= Shaped desired link angle
s	= Differential operator
t_i	= Time of the *i*th impulse
ζ	= System damping ratio
θ	= Motor angle
τ	= System input torque
ω	= Natural frequency
ω_0	= average of the natural frequency
ω_{max}	= Maximum of the natural frequency
ω_{min}	= Minimum of the natural frequency

I. Introduction

Recently, NASA announced an aspiring news that Voyager 1 finally became the first manmade space probe to travel out of the solar system after more than 36 years long journey. However, not every manmade objects in space has such a long lifespan. Human space exploration history was started from 1957 when Soviet Union launched the world's first manmade satellite into space. Since then, thousands of satellites from more than 50 countries have been launched into orbits around the Earth and other bodies including the Moon, Mercury, Venus, Mars, Jupiter, Saturn, Vesta, Eros, and the Sun. Among those orbiting the Earth, only a few hundred satellites are currently functional and operational, while thousands of non-functional satellites, spent rockets and satellite/rocket fragments orbit the Earth as space debris. Consequently, extending the lifespan of satellites and disposing the space debris in space become an active research topic in space engineering. Furthermore, with the fast development of space exploration over the past few decades, the operation and maintenance of space stations and other assets in space become a significant part of the space missions. Currently, the lifespan of a satellite is mainly limited by its fuel capacity. If refueling operation can be conducted, the lifespan of a satellite can be greatly extended. This kind of operations and other docking, assembling, repairing and disposing operations require high accuracy capture of the targets. Manual control of the capture operations from ground base suffers from long time delay, while sending astronauts into space to conduct the missions may induce higher cost and even the possibility of life loss. To assist human activities in these space exploration missions, robotic manipulators have been increasingly employed in constructing, repairing and other maintenance operations.

Currently robotic manipulators performed in space mainly in four types of missions: the International Space Station (ISS), the Mars Exploration Rovers (MER), the Orbital Docking System (ODS) and the Pure Experimental System (PES). The Mobile Servicing System (MSS, or Canadarm2), Japanese Experiment Module Remote Manipulator System (JEMRMS) and European Robotic Arm (ERA) are excellent examples of space robotic manipulators performed on ISS. These robotic manipulators are mainly for assembly, maintenance and payloads exchanging which can be conducted autonomously as well as operated by the astronauts. Robotic manipulators of MER, such as those mounted on the landers of Viking 1 and 2, Spirits and Opportunity, Phoenix and Curiosity are usually used to dig into the ground of the Mars, collect soil samples and/or position instruments on a target. They are performed by pre-programmed scripts when receiving the tele-operation commands sent from the Earth and/or relayed by the Mar Orbiter. Cameras mounted on these robotic manipulators are mostly used to monitor the movements of the manipulators and take photographs of the surroundings. Robotic manipulators of ODS, such as the Shuttle Remote Manipulator System (SRMS, or Canadarm) mounted on spacecraft, and the robotic manipulators mounted on Orbital Express, are usually performing grappling, docking, refueling, repairing and/or servicing another orbiter. These operations are called On-Orbit Servicing (OOS), which includes installation, maintenance and repair work on an orbital object in space. OOS is an emerging technology that promises to be a key element in the future of space exploration. For ROTEX and ETS-VII of PES, operations such as assembling, grasping, docking and other orbit-replaceable-unit (ORU) exchanging operations had been done to demonstrate the effectiveness of newly developed principles. A comparative study of space robotic manipulators is as shown in Table 1. It shows that robotic manipulators in space currently are without intelligence, and most of them employ human-in-the-loop control, which lay the majority of the decision-making and guidance into human hands.

This paper consists of 4 sections. After the brief review in this section, Section 2 discusses the challenges in the operation of space robotic manipulators. Then, we looked into the intelligent control theory for robotic manipulators to capture a non-cooperative target. In Section 3, a hybrid input shaping-based impedance controller has been proposed to suppress the residual vibration of the robotic manipulator with variable flexible joints. Numerical simulation and experimentation have also been done to demonstrate the effectiveness of the proposed control scheme. Finally, Section 4 concludes the paper.

II. Challenges

Many challenges have been encountered in controlling robotic manipulators. The manipulators are generally formed by a sequence of link and joint combinations. Control of a robotic manipulator refers to the control of each joint position in order to achieve a desired pose or trajectory of the end effector. Generally, the control input is the desired pose/trajectory of the end effector. Therefore, a controller needs to work out the desired position of each joint first and then drives the robotic manipulator to the desired pose/trajectory by controlling the torque of the joint motors. Because the number of links is usually more than three with redundant degrees of freedom, the control of space robotic manipulators is a multiple-solution problem. Furthermore, flexibilities are always exist [1-5]. On the one hand, in order to reduce the weight of space robotic manipulators in achieving large working space, long and thin links are usually used that inevitably induced link flexibility into the system. On the other hand, transmission devices, such as gearboxes, are used on the joint actuation to obtain sufficient driving torque and shaft couplings are used to adapting the coaxial errors between two jointed links. These transmission devices and shaft couplings will result in unwanted joint flexibilities. Nevertheless, the target is usually not static in the space. Thus, the trajectory planning of the end effector approaching a moving target is also a multiple-solution problem. Researchers have developed various control schemes. However, there is still a vast field to be explored in the intelligent control theory of space robotic manipulators.

The manipulation process of target capturing for robotic manipulators requires not only the development of advanced controllers with consideration of realistic constraints such as flexibilities and mechanical limitation but also the trajectory planning problem that considers optimal time/energy consumption. Therefore, the robotic control problem can be divided into two parts, trajectory planning and motion control. Trajectory planning [6-12], which is some kind of decision making, will provide a desired trajectory of the end effector. Motion control [13-33], which is the decision executor, is a key premise of a successful capture motion. A premise is both trajectory planning and motion control will be relied on feedback systems, such as sensors. Feedback systems provide the essential information of the system, which can be used to calculate or estimate the pose and trajectory of the end effector and the target.

2.1 Vision System

Vision is highly favored in feedback system as it is a non-intrusive, non-damaging and non-contact method. The use of a camera in a robot control loop can be performed with two types of architecture: eye-in-hand and eye-to-hand [34]. In the eye-in-hand configuration, the camera is rigidly mounted on the robotic arm in the vicinity of the end effector, while the eye-to-hand camera is fixed in workspace to observe the robot and the target. The eye-in-hand configuration gives a limited but more accurate feedback of the local environment of the task. However, it is hard to obtain global information, which is disadvantageous when dealing with global trajectory planning problems. The eye-to-hand configuration can provide global but less precise information of the robot and target relative to the environment, which is preferable for the trajectory planning. However, local information can't be obtained directly. Sometimes eye-in-hand and eye-to-hand cameras are used at the same time to obtain more confident environment information of both local and global.

2.2 Intelligent Trajectory Planning

In order to develop a trajectory for the end effector, intelligent control is adopted due to the multiple solution problems, where various artificial intelligence computing approaches are employed, such as neural networks, fuzzy logic and genetic algorithms. Artificial neural networks [35] consist of massively connected set of neurons that mimics biological neural networks. The feed-forward multilayer neural network is the most widely used among artificial neural networks in intelligent control system applications. One of the advantages

Table 1. Comparative Study of Space Robotic Manipulators.

Name	Date	Agency	Size & DoFs	Vision System	Operation Approach	Features
Landers of Viking 1 and 2	1975-1982	NASA	10 feet, 120° radius.	Two 360° cylindrical scan cameras	Pre-programmed and Tele-operation (from Earth, relayed by the Mar Orbiter)	The arm with a collector head, temperature sensor, and magnet on the end, was used to dig into the ground and taking out samples of Martian soil.
Canadarm	1981-2011	NASA	15.2 meters, 6 DoFs.	One at the elbow joint and one at the wrist joint.	Autonomous operation or astronaut control	The Canadarm was used on the space shuttle. In all, five arms were built and delivered. Three arms are currently in operation.
ROTEX	April-May, 1993	DLR	workspace: 1m, 6 DoFs.	Two stereo cameras on the end effector, two fixed cameras	Tele-operation (on board or from ground) or pre-programmed autonomous operation	Three basic tasks were successfully performed: assembling a mechanical truss structure, connecting/disconnecting an electrical plug and grasping a floating object.
ETS-VII	1997-2002	NASDA (JAXA)	2 meters, 6 DoFs.	Two hand cameras, two shoulder cameras.	Tele-operation (from Earth, 5-7 seconds of time delay)	The robotic arm was attached to the chaser satellite of ETS-II.
Canadarm2	2001-now	NASA	17.6 meters, 7 DoFs.	Four color cameras	Autonomous operation or astronaut control	The Canadarm2 with no fixed end, consists by 3 parts: the manipulator, the Mobile Remote Servicer Base System (MBS) and the Special Purpose Dexterous Manipulator (SPDM).
Spirit and Opportunity	2004-now	NASA	5 DoFs	One microscopic imager on the arm.	Pre-programmed and Tele-operation (from Earth, relayed by the Mar Orbiter)	The arm carries multiple instruments, and is used to position these instruments on a target. 1 Panoramic Cam, 1 Navigation Cam, 2 B&W Hazard Avoidance Cams mounted on the rover.
Orbital Express	March-July, 2007	DARPA & MSFC	3 meters 6 DoFs	One camera mounted at the end effector.	Autonomous (by executing pre-planned scripts, no intelligent)	Orbital Express is demonstrating the technologies required for on-orbit servicing. The arm is for grapple, dock, refuel, repair and service another satellite.
JEM Remote Manipulator System	2008-now	JAXA	Main Arm: 9.91 m, 6 DoFs Small Fine Arm: 2.2 m, 6 DoFs	Two cameras mounted on the main arm.	Astronaut control	The Main Arm is used for exchanging EF (Exposed Facility) payloads. The SFA handles small items.
Phoenix	May-Nov., 2008	NASA	2.35 meters 4 DoFs	One full-color camera attached above the scoop.	Pre-programmed and Tele-operation (from Earth, relayed by the Mar Orbiter)	The arm has the ability to dig down to 0.5 m below the surface.
European Robotic Arm (ERA)	2010-now (still in building)	ESA	11.3 meters 7 DoFs	Four Camera and Lighting Units (CLU)	Autonomous operation or astronaut control	ERA can walk around the ISS under its own control, hand-over-hand between base points. Astronauts can control it from inside or outside the Station.
Curiosity (The lander of Mars Science Laboratory)	Aug., 2012 (landing)	NASA	2.3 meters 5 DOFs	It has 17 cameras: HazCams (8), NavCams (4), MastCams (2), MAHLI (1), MARDI(1), and ChemCam (1).	Pre-programmed and Tele-operation (from Earth, relayed by the Mar Orbiter)	One set of moves has never been tried before on Mars: pulling pulverized samples from the interior of Martian rocks and placing them into laboratory instruments inside the rover. The arm has two joints at the shoulder, one at the elbow and two at the wrist.

LEGEND of TABLE 1

Color	Representative
(dark grey)	→ Robotic Manipulators of ISS
(light grey)	→ Robotic Manipulators of MER
(medium grey)	→ Robotic Manipulators of ODS
(grey)	→ Robotic Manipulators of PES

of neural networks is their learning ability, where a cost function is defined to measure how far away a solution is from an optimal solution. Learning algorithms are aim to find a solution that has the smallest cost. The main advantage of neural networks is that they can find solutions which are asymptotic to the optimal solution by machine learning and they do not need to know the dynamic models of robotics. However, a drawback of neural networks is that they require a large diversity of training for real-world operation. Fuzzy logic [36] is a methodology using prior experience to control a system. In general, the fuzzy controller has four components: the rule-base, fuzzification, decision making and defuzzification. Fuzzy logic is easy to understand and the rules are set in advance. However, since the rule-base construction is based on the designer's prior experience of the control system, it will be very complex when dealing with practical application. Genetic algorithm (GA) [37] is a search heuristic that mimics the characteristics of evolution, natural selection (Darwin), and genetics (Mendel). A typical genetic algorithm requires a group of randomly multifarious solutions or population, a fitness function to evaluate every solution in the population and reproduction operators (mutation, crossover, inversion and selection) to generate new generations. An advantage of GAs is that it can be used to optimize a solution when the optimal solution is not clearly known or defined. However, the final solution is only in comparison to other solutions within the population, and GAs may have a tendency to converge towards local optima.

2.3 Motion Control Theory

In the past several decades, many efforts have also been devoted to the motion control of both rigid and flexible robotic manipulators. Many sorts of robot control schemes have been proposed. One way to classify these control schemes is to divide them into computed-torque-like and non-computed-torque-like [13]. The impedance control theory, proposed by Hogan in 1985 [14], is a kind of computed-torque-like control theory and is regarded as the most effective control theory for robotic manipulators interacting with the environment [15-23]. However, impedance control is based on the dynamic model of plant. Unknown variable flexibilities produces variable dynamic model, which weakens the performance of the impedance controller. Input shaping [38-44] is particularly effective for suppressing motion-induced vibration in flexible systems. However, the open-loop structure of input shaping indicates it is prone to environmental disturbances. Close-loop input shaping requires exact model of the plant. Using approximate model may weaken the performance or even destabilize the system.

III. Motion Control of Flexible Joint Robotic Manipulators

In this work, we propose a hybrid controller for the motion control of a single rigid link flexible joint robotic manipulator. The first part is an open-loop input shaper. Instead of requiring the exact knowledge of joint flexibility (or system natural frequency), the input shaper is designed based on a range of system natural frequencies that are due to the variation of joint flexibility in operation. It will shape the initial command (step input) to a stair-step signal by convolving the initial command with a series pulses. Then, this stair-step signal will be used as the new input command for the close-loop system in the second part. As a result, the response vibration caused by each stair-step will be cancelled by each other. The second part is a closed-loop impedance controller. Instead of considering system transfer function, impedance control is designed based on the system dynamic model and a predefined objective impedance function, which not only simplifies the controller design, but also gives us some accessible virtual physical meanings. The proposed impedance controller is based on a simplified dynamic model of the robotic manipulator by ignoring the variation of joint flexibility, and controls the flexible joint robotic manipulator to the desired performance. This two part approach is advantageous by separating the vibration suppression and robotic motion control. It is more flexible in dealing with the robotic manipulator with variable joint flexibility. Numerical simulation and experimentation have also been done to validate the proposed control scheme.

3.1 Dynamics of Robotic Manipulator

Regarding driving torque of the motor as system input and without consideration of system damping and friction, the dynamic equation of the rigid link flexible joint robotic manipulator is as,

$$\begin{cases} J\ddot{q} + J_m\ddot{\theta} = \tau \\ J\ddot{q} + K(q-\theta) = 0 \end{cases} \tag{1}$$

where q is the link angle, θ is the motor angle, τ is the control input torque, K is the stiffness of the flexible joint, J is the inertia of the link and J_m is the inertia of the motor. Once we have the dynamics, we are ready to design the controller.

In fact, the driving torque of servo motor is usually not directly controlled, relatively, position control is more common. Therefore, we consider the motor angle as system input and link angle as the output, the dynamic equation of the single rigid link flexible joint robotic manipulator is as,

$$J\ddot{q} + K(q-\theta) = 0 \tag{2}$$

3.2 Input Shaping Control Scheme

If the natural frequency, ω, and damping ratio, ζ are known, then the percentage residual vibration [38] that results from a sequence of impulses can be described by,

$$PRV(\omega,\zeta) = e^{-\zeta\omega t_n}\sqrt{\left(\sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\cos\left(\omega\sqrt{1-\zeta^2}\,t_i\right)\right)^2 + \left(\sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\sin\left(\omega\sqrt{1-\zeta^2}\,t_i\right)\right)^2} \tag{3}$$

In our case we have a variable joint stiffness which will induce a variable natural frequency of vibrations to the dynamic system. Assuming we know the variation range of the natural frequency, then we may further define the average natural frequency as,

$$\omega_0 = \frac{\omega_{\min} + \omega_{\max}}{2} \tag{4}$$

For the purpose of suppressing this residual vibration, a two-hump EI shaper is designed based on reference [39]. Define V as the percentage vibration, T_d as the period of the vibration, such that,

$$A_1 = A_4 = \frac{3\left(\sqrt[3]{V^2\left(\sqrt{1-V^2}+1\right)}\right)^2 + 2\sqrt[3]{V^2\left(\sqrt{1-V^2}+1\right)} + 3V^2}{16\sqrt[3]{V^2\left(\sqrt{1-V^2}+1\right)}} \tag{5}$$

$$A_2 = A_3 = \frac{1}{2} - A_1 \tag{6}$$

$$T_d = \frac{2\pi}{\omega_0\sqrt{1-\zeta^2}} \tag{7}$$

Therefore, the two-hump EI shaper is given by,

$$P = \begin{bmatrix} A_1 & A_2 & A_3 & A_4 \\ 0 & 0.5T_d & T_d & 1.5T_d \end{bmatrix} \tag{8}$$

3.3 Impedance Controller

An impedance controller can be designed both in Cartesian space and joint space. Most of the robotic manipulator has more than one link and the manipulation is always done by the end effector. Thus, most of the impedance controllers are designed in the Cartesian space. For our case, since the purpose is to perform accurate positioning as well as suppress the vibration of the single link manipulator, we designed an impedance controller in joint space for simplification. Assume there is no interacting between the manipulator and the environment in our case, the desired steady state is the motor angle and the link angle both approaching the desired link angle. Therefore, define the impedance function as,

$$m\left(\ddot{q}_d - \ddot{q}\right) + b\left(\dot{q}_d - \dot{q}\right) + k\left(q_d - q\right) = 0 \tag{9}$$

From Eq. (9) we have:

$$\ddot{q} = \ddot{q}_d + \frac{b}{m}\left(\dot{q}_d - \dot{q}\right) + \frac{k}{m}\left(q_d - q\right) \tag{10}$$

Then according to the dynamics equation as shown in Eq. (2), the impedance control law can be easily obtained as,

$$\theta = q + \frac{J}{K}\left(\ddot{q}_d + \frac{b}{m}\left(\dot{q}_d - \dot{q}\right) + \frac{k}{m}\left(q_d - q\right)\right) \tag{11}$$

3.4 Simulation

The proposed controller has been validated by numerical simulation. Diagram of the proposed control scheme is as shown in Figure 1. The simulation results are as shown in Fig. 2 and 3. Figure 4 shows the input motor angle. As a comparison, the result of pure impedance control, pure input shaping and no control are also included. Due to the combination of both input shaping and impedance control, the newly proposed controller induced more time delay. However, it reduced the driving torque requirement of the motor and suppressed the vibration significantly, which is more desirable.

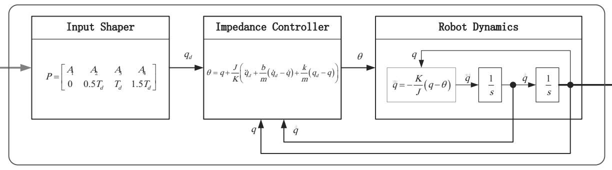

Figure 1. Diagram of the proposed hybrid control scheme.

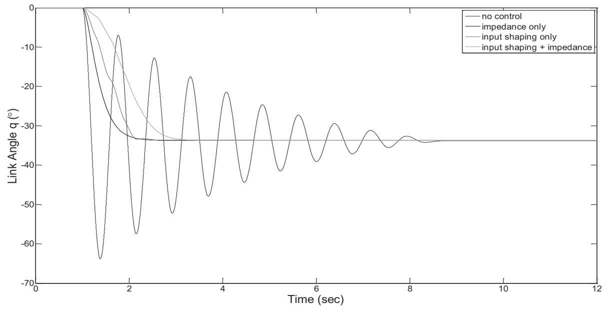

Figure 2. Simulation result of link angle.

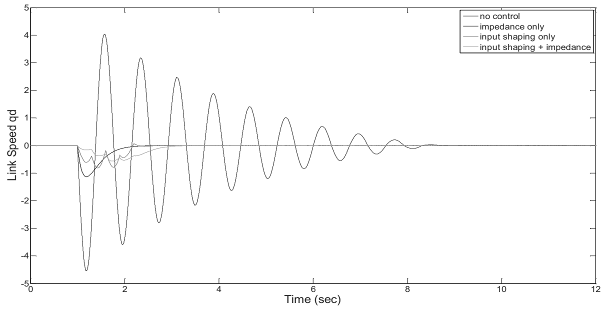

Figure 3. Simulation result of link speed.

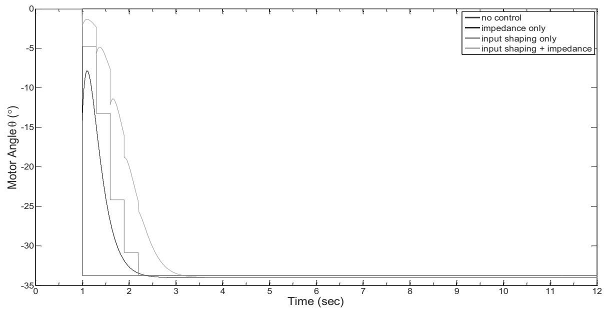

Figure 4. Input motor angle.

3.5 Experimental Validation

Once the computer simulation proves the validity of the new controller, a single rigid-link flexible-joint robotic manipulator was designed and built to demonstrate the effectiveness of the new controller. Figure 5 shows the experimental setup and Figure 6 shows the experimental results of the proposed control scheme.

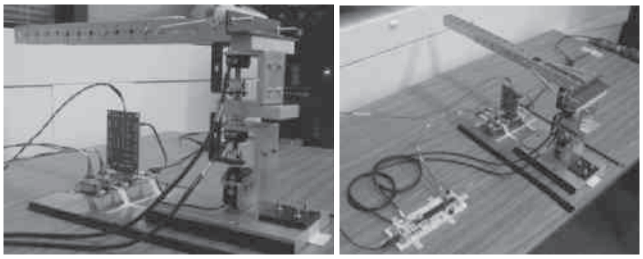

Figure 5. Single rigid link flexible joint robotic manipulator test system.

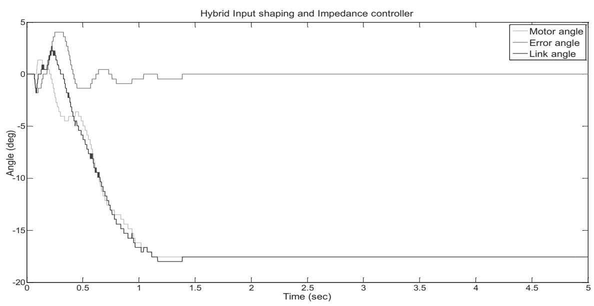

Figure 6. Experimental results of proposed control scheme.

From the figures we can see the proposed control scheme successfully suppressed the vibration of the link. Although a disadvantage of the proposed control scheme that it will induce a time delay by input shaping, the proposed two-part control scheme is effective and easier to design than those controllers which considered the whole system dynamics.

IV. Conclusion

In this paper, we proposed a hybrid input shaping-based impedance controller to suppress the residual vibration of the robotic manipulator with variable flexible joints. The proposed controller consists of two parts: an open-loop input shaping and a close-loop impedance control. Compared with each of the controller, the new controller is easy to derive and robust to environment disturbance. The computer simulation and experimentation show the controller is working well.

V. Acknowledgments

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Note: Nominations must be received by the 15th of November for awards and fellowships to be conferred in March of the following year

Instructions for Nominators to complete the Nomination Package:

1. Identify a member of an EIC member society as a nominee for an EIC Fellowship or Award, and obtain a copy of his or her resume or curriculum vitae (CV). The nominee should not know that he or she is being nominated for an EIC Fellowship or Award. Refer to http://www.eic-ici.ca/english/tour/haf2.html and click on the award of interest for the terms of reference. Note that nominators must be members of an EIC Member Society.

2. Identify two or three people who may, but need not be, members of an EIC Member Society and who know the nominee. Seek their agreement to serve as supporters of the nominee in the form of a letter. These letters of support should be 1 to 2 pages in length and convey the supporter's knowledge, experience and personal interaction with the nominee. The letters should also indicate the e-mail address and position of the supporter

3. Complete this Nomination Form in its entirety and note that a 150 - 200 word citation must be included in the space provided. To review previous citations go to http://www.eic-ici.ca/english/tour/haf2.html and click on the relevant award, then click on Citation where it appears beside a recipient of interest. The citation should describe the **importance and impact of the nominee's accomplishments**. The selection committee is much less interested in quantity of work that it is in quality as measured by impact of the work on engineering society etc.

4. Note that, except for the Honorary Member Award, EIC recognition is for members of Member Societies of the EIC only. Honorary members need not be engineers but engineers are not excluded.

5. When the nomination package is complete, e-mail it to jplant1@cogeco.ca or send a hard copy by courier to John Plant, Executive Director, EIC, 1295 Hwy 2 E, Kingston ON K7L 4V1. In summary before 15 November 2013, the Nomination Package for a nominee includes the following documentation:

- The completed Nomination Form;
- A minimum of two (2) or a maximum of three (3) letters of support; and,
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