Cover Page for Proposal Submitted to the National Aeronautics and Space Administration

NASA Proposal Number

TBD on Submit

NASA PROCEDURE FOR HANDLING PROPOSALS

This proposal shall be used and disclosed for evaluation purposes only, and a copy of this Government notice shall be applied to any reproduction or abstract thereof. Any authorized restrictive notices that the submitter places on this proposal shall also be strictly complied with. Disclosure of this proposal for any reason outside the Government evaluation purposes shall be made only to the extent authorized by the Government.

SECTION I - Proposal Information

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Provo	**UT**	**84601-4356**	**US**

Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**

Proposed Start Date	Proposed End Date	Total Budget
08 / 01 / 2017	**08 / 01 / 2018**	**No budget required**

SECTION II - Application Information

NASA Program Announcement Number	NASA Program Announcement Title
NSTRF17	**NASA Space Technology Research Fellowship (NSTRF) - Fall 2017**

For Consideration By NASA Organization *(the soliciting organization, or the organization to which an unsolicited proposal is submitted)*

NASA , Headquarters , Space Technology Mission Directorate , Space Technology Research Grants

Date Submitted	Submission Method	Grants.gov Application Identifier	Applicant Proposal Identifier
	Electronic Submission Only		

Type of Application	Predecessor Award Number	Other Federal Agencies to Which Proposal Has Been Submitted
New		**National Science Foundation (NSF)**

International Participation	Type of International Participation
No	

SECTION III - Submitting Organization Information

DUNS Number	CAGE Code	Employer Identification Number (EIN or TIN)	Organization Type
999999911	**ZZZ11**		**2A**

Organization Name (Standard/Legal Name)	Company Division
NSTRF Proposal Submission Office	

Organization DBA Name	Division Number
NSTRF Proposal Submission Office	

Street Address (1)	Street Address (2)
2345 Crystal Drive	**NRESS IT**

City	State / Province	Postal Code	Country Code
Arlington	**VA**	**22202**	**USA**

SECTION IV - Proposal Point of Contact Information

Name	Email Address	Phone Number
Dustan Kraus	**dustan.kraus@gmail.com**	**208-540-0284**

SECTION V - Certification and Authorization

Certification of Compliance with Applicable Executive Orders and U.S. Code

By submitting the proposal identified in the Cover Sheet/Proposal Summary in response to this Research Announcement, the Authorizing Official of the proposing organization (or the individual proposer if there is no proposing organization) as identified below:

- certifies that the statements made in this proposal are true and complete to the best of his/her knowledge;
- agrees to accept the obligations to comply with NASA award terms and conditions if an award is made as a result of this proposal; and
- confirms compliance with all provisions, rules, and stipulations set forth in this solicitation.

Willful provision of false information in this proposal and/or its supporting documents, or in reports required under an ensuing award, is a criminal offense (U.S. Code, Title 18, Section 1001).

Authorized Organizational Representative (AOR) Name	AOR E-mail Address	Phone Number

AOR Signature *(Must have AOR's original signature. Do not sign "for" AOR.)*	Date

PI Name : **Dustan Kraus**		NASA Proposal Number
Organization Name : **NSTRF Proposal Submission Office**		TBD on Submit
Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**		

SECTION VI - Team Members

Team Member Role	Team Member Name	Contact Phone	E-mail Address
PI	**Dustan Kraus**	**208-540-0284**	**dustan.kraus@gmail.com**

Organization/Business Relationship	Cage Code	DUNS#
NSTRF Proposal Submission Office	**ZZZ11**	**999999911**

International Participation	U.S. Government Agency	Total Funds Requested
No		**0.00**

PI Name : **Dustan Kraus**	NASA Proposal Number
Organization Name : **NSTRF Proposal Submission Office**	TBD on Submit
Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**	

SECTION VII - Project Summary

Industrial robots, though highly precise and capable, have a relatively high inertia. This severely limits how quickly and safely they can move to avoid unexpected collisions and high impact forces while operating in close proximity to humans and delicate equipment. Furthermore, the high mass of these robots results in a higher robotic payload in space applications. My research will focus on soft, pneumatically actuated robots that will use comparatively less payload (weighing ten times less than Robonaut 2) and be safer around people and equipment than traditional robots, even when moving at high speeds.

One important feature in robots capable of working around humans and mimicking human dexterity is the ability to use two or more arms. Many tasks such as lifting heavy/bulky objects or service and assembly are difficult, if not impossible, with only one arm. This problem has sparked research into multi-arm manipulation. My research will focus on coordinated, multi-arm manipulation using inflatable, pneumatically actuated robots. Coordinated manipulation tasks are defined as two or more robotic arms physically interacting with the same object. My hypothesis is that coordinated multi-arm manipulation can realistically and usefully be implemented with an inflatable, pneumatically actuated robot. My research goals are to implement coordinated multi-arm control for (1) impact tasks with rigid objects (like sweeping off a solar panel or assembly of construction materials that require impact for insertion) and (2) soft object manipulation tasks (like moving a tarp or a flexible solar array).

Accomplishing my research goals will require several steps. One difficulty with soft, robotic arms is that the dynamics and kinematics of the arm change regularly. This makes it difficult to accurately and repeatably reach a desired position. My first approach to this challenge will be to design a hybrid controller using model predictive control and servoing to close task space error. Once I can accurately command a single arm, my approach to coordinated multi-arm manipulation will be to design and implement an object level model predictive controller to accurately control both rigid and soft objects. With this design, I propose that each arm can be treated as a force/torque input on the object.

This research has many applications to NASA interests and programs. The NASA Technology Roadmap TA 4.3.5: Collaborative Manipulation states, “For collaborative manipulation, the required technical capability is to provide a teamed approach for multiple robots or teams of humans and robots working with objects, equipment, or samples.” This collaboration includes coordinated manipulation tasks where multiple robot manipulators are physically connected together in tasks like handling a common load. My graduate research directly impacts these goals. I will be researching and implementing control methods for coordinated multi-arm manipulation tasks with soft robots. This research will enable soft robots to work collaboratively with other robots (soft and rigid) on tasks in space. Furthermore, TA 4.3.5 lists robust safety system development as a goal. TA 4.7.5: Safety and Trust expands on this by setting the goal of having a crew “be able to work next to a robotic assistant, within a one-meter proximity in a controlled and safe manner, without being physically attached to it.” The soft robotic platforms I will be utilizing for my research are inherently safe for operation around humans and delicate equipment due to their inflatable structure and low inertia. The algorithms I develop for multi-arm manipulation will help these robots have performance on par with state of the art torque controlled robots to work more robustly and safely in space.

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Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**

SECTION VIII - Other Project Information

Proprietary Information

Is proprietary/privileged information included in this application?

Yes

International Collaboration

Does this project involve activities outside the U.S. or partnership with International Collaborators?

No

Principal Investigator	Co-Investigator	Collaborator	Equipment	Facilities
No	**No**	**No**	**No**	**No**

Explanation :

NASA Civil Servant Project Personnel

Are NASA civil servant personnel participating as team members on this project (include funded and unfunded)?

No

Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year	Fiscal Year
Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs	Number of FTEs

PI Name : **Dustan Kraus**	NASA Proposal Number
Organization Name : **NSTRF Proposal Submission Office**	TBD on Submit

Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**

SECTION VIII - Other Project Information

Environmental Impact

Does this project have an actual or potential impact on the environment?	Has an exemption been authorized or an environmental assessment (EA) or an environmental impact statement (EIS) been performed?
No	**No**

Environmental Impact Explanation:

Exemption/EA/EIS Explanation:

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SECTION VIII - Other Project Information

Historical Site/Object Impact

Does this project have the potential to affect historic, archeological, or traditional cultural sites (such as Native American burial or ceremonial grounds) or historic objects (such as an historic aircraft or spacecraft)?

No

Explanation:

PI Name : **Dustan Kraus**	NASA Proposal Number
Organization Name : **NSTRF Proposal Submission Office**	TBD on Submit

Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**

SECTION IX - Program Specific Data

Overall Instructions: Questions that are marked with a green asterisk (*) indicate that a response is required. You must answer all the required questions for NSPIRES to save your work.

Selection of TABS element: Questions 1 and 2 allow you to specify and explain the level 2 TABS element(s) most closely associated with your application. Question 2 requires a thorough justification for your selection in response to Question 1. Please refer to the actual roadmap documents to gain an understanding of what each level 2 element is seeking; do not rely on the level 2 TABS titles. The complete TABS, including all level 1, 2 and 3 elements, may be found in NSTRF17_TABS.pdf. This document includes notes on several level 3 TABS elements that were impacted during the 2015 update of the roadmaps; these notes are intended to summarize, at a high level, possible changes in scope of the associated level 2 TABS elements. Your input may be considered during the application evaluation process.

Question 1 : Please select the level 2 TABS element most closely associated with your application.

Answer: 4.3 Manipulation

Question 2 : Please provide a thorough justification for your selection in Question 1. Whenever possible, please specify the appropriate level 3 TABS element in response to this question. It is permissible to specify other relevant TABS elements in the roadmap documents; however, the applicant is encouraged to spend his/her time identifying the best match, rather than declaring widespread applicability. Note: Project Narratives must be specifically focused on low TRL space technology; Project Narratives which are focused on science investigations to inform technology development or the use of existing technologies to conduct science investigations will be deemed non-compliant and not be submitted for review.

Answer:

A sub-goal of TA 4.3: Manipulation is to increase manipulator dexterity while reducing overall mass and launch volume and increasing power efficiency. I will be focusing on coordinated multi-arm manipulation tasks with inflatable, soft robots for my graduate research. These soft robots are an order of magnitude lighter and occupy 10 times less volume when deflated than current state of the art torque controlled robots (like Robonaut 2). A single soft robot may not have the power output of the current generation of torque controlled robots, but these soft robots have such a low weight and volume that it would still drastically reduce the overall launch mass and volume to send multiple soft robots on space missions. My research will make this feasible by enabling multiple soft robots to collaborate with each other or even humans on the same manipulation task. This directly contributes to the goal of TA 4.3.
More specifically, TA 4.3.5: Collaborative Manipulation states, "For collaborative manipulation, the required technical capability is to provide a teamed approach for multiple robots or teams of humans and robots working with objects, equipment, or samples." This collaboration includes coordinated manipulation tasks (where multiple robot manipulators are physically connected together in tasks like handling a common load). My graduate research on multi-arm manipulation with soft robots directly contributes to this goal. My research goals are to (1) implement coordinated control for impact task with rigid objects (like sweeping off a solar panel, assembly of construction materials that require impact for insertion, or hammering) and (2) implement coordinated control for soft object manipulation tasks (like moving a tarp or a flexible solar array).
Furthermore, TA 4.3.5 lists robust safety system development as a goal. TA 4.7.5: Safety and Trust expands on this by setting the goal of having a crew "be able to work next to a robotic assistant, within a one-meter proximity in a controlled and safe manner, without being physically attached to it." The soft robotic platforms I will be using for my research are inherently safe for operation around humans and delicate equipment due to their inflatable structure and low inertia. The algorithms I develop will help these robots have performance on par with state of the art torque controlled robots so that they will work more robustly and safely in close proximity to humans.

Demographic Information

Question 3 : Gender

Answer: Male

Question 4 : Are you an individual with disabilities?

Answer: No

Question 5 : Race/Ethnicity - Please check all that apply
Answers :

White, not of Hispanic Origin

Question 6 : Birth Month

Answer: 02

Question 7 : Birth Year

Answer: 1991

Question 8 : Birth City

Answer: Lewiston

Question 9 : U.S. Birth State or Territory

Answer: Idaho

Question 10 : Birth Country

Answer: United States (U.S.)

Eligibility and Years of Support Sought

Question 11 : Are you a U.S. citizen or permanent resident alien of the U.S.?

Answer: Yes

Question 12 : If you are not a U.S. citizen, please provide your country of citizenship.

Answer: Please select from list

Question 13 : Are you the current or past recipient of a graduate federal fellowship or scholarship?

Answer: No

Question 14 : If your answer to Question 13 is Yes, please identify the graduate fellowship or scholarship (name of sponsoring federal agency and name of fellowship) and provide the number of years of support that you will have received prior to the fall 2017 term. If your answer to Question 13 is No, please type N/A.

Answer: N/A

Question 15 : Are you currently part of or have you applied to the NASA Pathways Program?

Answer: No

Question 16 : If your answer to Question 15 is Yes, please provide a specific explanation. If your answer to Question 15 is No, please type N/A.

Answer: N/A

Question 17 : Have you previously applied for a NASA Space Technology Research Fellowship? If so, please select the appropriate solicitation(s) from the list below. Note: a student requesting doctoral support under NSTRF17 will not be eligible if they have applied for doctoral support under two previous NSTRF solicitations, unless they were an undergraduate student at the time of a previous application submission (see Section 4 - Eligibility). If you have never requested support under a NASA Space Technology Research Fellowship, please select N/A.

Answers :

NSTRF16 - NASA Space Technology Research Fellowships (NSTRF) - Fall 2016

Question 18 : Are you currently an undergraduate student?

Answer: No

Question 19 : Month that your bachelor's degree was, or is expected to be, received

Answer: 04

Question 20 : Year that your bachelor's degree was, or is expected to be, received.

Answer: 2016

Question 21 : Month that you began any graduate studies. Select N/A if you are currently an undergraduate or have not yet commenced any technical graduate studies.

Answer: 08

Question 22 : Year that you began any graduate studies. Select N/A if you are currently an undergraduate or have not yet commenced any technical graduate studies.

Answer: 2016

Question 23 : Degree which you are seeking under this fellowship. Note: students just beginning their graduate studies with the goal of receiving a doctoral degree may select "Doctoral" below even if their university requires them to obtain a master's degree first. The application submitted must cover the entire intended period of study (with a single, continuous research topic).

Answer: Master's

Question 24 : Total number of years of NSTRF support sought (partial years are permitted). Please see Section 5 - Terms and Conditions of the NSTRF17 solicitation for clarification and special considerations. The number of years sought must include the initial year plus all desired renewal years. Note 1: Students seeking master's degree support are eligible for a maximum of 2 years of support. Note 2: Please note special considerations for students seeking doctoral support and students who are current or former recipients of other graduate federal fellowships or scholarships.

Answer: 1

Question 25 : Month that you expect to receive the degree for which you are seeking support under NSTRF17.

Answer: 08

Question 26 : Year that you expect to receive the degree for which you are seeking support under NSTRF17.

Answer: 2018

Question 27 : Please select your eligibility profile, as specified in Section 4 - Eligibility of the NSTRF17 solicitation.

Answer: Profile 1 - Entering Master's Student

Question 28 : Please point to specific data in your application (cite details) to substantiate your answer to Question 27. Your transcript must clearly show that a master's degree has been conferred if you select Profile 3.

Answer:

As shown on my transcript, I graduated Cum Laude with my bachelor's degree in mechanical engineering in April 2016. I began my master's degree in August 2016 and am currently enrolled in graduate classes (this is also shown on my transcript as it shows the classes I am currently enrolled in).

Question 29 : If your response to Question 27 was Profile 3, please explain in technical terms why your master's degree represents a non pro forma milestone. Type N/A if you selected another profile.

Answer:

N/A

Graduate and undergraduate Grade Point Averages (GPAs), past and current academic departments and universities

Question 30 : Undergraduate GPA

Answer: 3.89

Question 31 : Undergraduate GPA Scale

Answer: 4.00

Question 32 : Institution from which you received your undergraduate degree. If you are currently an undergraduate student, please enter the institution you are attending.

Answer: Brigham Young University

Question 33 : Undergraduate academic department

Answer: Mechanical Engineering

Question 34 : Graduate GPA

Answer: N/A

Question 35 : Graduate GPA Scale

Answer: N/A

Question 36 : Institution in which you are currently enrolled for graduate study. If you are currently an undergraduate student, please enter N/A

Answer: Brigham Young University

Question 37 : Graduate academic department

Answer: Mechanical Engineering

The NSTRF17 solicitation requires you to discuss your choice of academic institution(s) as part of the Personal Statement. Questions 38-40 allow you to specify the university or universities that you are considering for the degree program for which you are requesting support. If you are already enrolled as a graduate student and you will continue to pursue your graduate studies at your current university in the fall of 2017, please do not reply N/A to Question 38 - please enter the name of your current university in response to this question. In addition, if you are certain of your fall 2017 graduate institution, enter N/A for Questions 39 and 40. Question 41 asks the name of your

fall 2017 faculty advisor, if known; enter N/A if not known. Question 42 asks you to specify your anticipated (or known) fall 2017 graduate academic department. Answers to all five questions are required.

Question 38 : The name of your first choice academic institution

Answer: Brigham Young University

Question 39 : The name of an alternate choice academic institution

Answer: N/A

Question 40 : The name of a second alternate choice academic institution

Answer: N/A

Question 41 : Fall 2017 graduate faculty advisor, if known.

Answer: Marc Killpack

Question 42 : Fall 2017 anticipated graduate academic department

Answer: Mechanical Engineering

Questions 43-50 of this section refer to the GRE General Test scores, a required part of your application (see Section 9 - Application Procedures - Phase A of the NSTRF17 solicitation). If you took the GRE General Test more than one time, you may choose which GRE scores to report, but all scores must be from the same GRE General Test date. If you did not take the GRE General Test, select N/A for your response to Question 43, provide an explanation in Question 44 and type or select N/A for your answer in response to Questions 45-50.

Question 43 : Please select the Verbal Reasoning and Quantitative Reasoning Score reporting scale on the test which you have chosen to provide.

Answer: 130-170, in 1 point increments

Question 44 : If your answer to Question 43 is N/A, provide an explanation why GRE scores are not available (e.g., were not required for graduate school admission). Enter "GRE scores are available" if you took the GRE General Test.

Answer: GRE scores are available

Question 45 : Verbal Reasoning GRE Score

Answer: 163

Question 46 : Verbal Reasoning GRE % Below

Answer: 92

Question 47 : Quantitative Reasoning GRE Score

Answer: 165

Question 48 : Quantitative Reasoning GRE % Below

Answer: 90

Question 49 : Analytical Writing GRE Score

Answer: 4.0

Question 50 : Analytical Writing GRE % Below

Answer: 56

PI Name : **Dustan Kraus**	NASA Proposal Number TBD on Submit
Organization Name : **NSTRF Proposal Submission Office**	
Proposal Title : **Control Methods for Coordinated, Multi-Arm Manipulation with Soft Robots**	

SECTION X - Budget

Total Budget: No budget required

1 Personal Statement

1.1 Preparation and Potential for Space Technology Research

Early in my education, I learned of the major impact space technology like satellites has on our personal lives. The researchers who developed this technology changed the world, and I longed to make similar impactful contributions to benefit mankind. This desire led me to pursue a bachelor's degree in mechanical engineering. During my undergraduate studies, I discovered that I had an aptitude for and love of controls and robotics. I found that the best way to get involved in robotics research that would benefit society was to pursue a graduate degree. Nelson Mandela said, "Education is the most powerful weapon which you can use to change the world". My education will empower me to positively influence the world through my career by performing cutting edge space technology research which will benefit society. The following sections highlight a few of the most prominent experiences that have prepared me to push forward the frontiers of space technology research in controls and robotics.

1.1.1 Los Alamos Dynamic Summer School – 2014

Los Alamos National Laboratory (LANL) was my first exposure to the world of research. In a disaster scenario, humans on foot can take a long time to navigate unsafe terrain to locate people who need help. Unmanned aerial vehicles (UAVs) are one of the most promising technologies in the effort to improve response times as they could quickly locate survivors and direct responders accordingly. In many disaster scenarios, UAVs would need to fly indoors to find people. One of the challenges of flying a UAV indoors via onboard visual feedback is encountering reflective and transparent barriers. Glass office partitions, windows, and mirrors can confuse the operator (or autonomous navigation system), reducing the ability to accurately identify the location of people in need of rescue. During this nine-week fellowship, I worked with two other students to design a multimodal sensing system capable of determining 1) whether a barrier was transparent, reflective, or opaque and 2) the distance and angle of approach to that barrier. I personally came up with the system architecture we ultimately chose to use, headed the mechanical design of our prototype, and designed and implemented the algorithms for determining the distance and angle of approach to the barriers.

By the end of the fellowship, we had built and tested a successful prototype. We also published our research in an SPIE conference paper [1], and I was selected to present our results at the SPIE conference. Working as a researcher at LANL left me amazed by the depth of knowledge my mentors possessed. They were able to guide us to the most viable solutions of our difficult research problems while performing impactful research of their own. During this experience, I developed a strong desire to become a technical expert so that I could also help younger researchers while contributing to the solutions of difficult problems.

1.1.2 BYU Tactile Sensor Development – 2015

After my experience at LANL, I sought out more research opportunities at Brigham Young University (BYU). Being particularly interested in dynamics and control, I decided to become involved with the BYU Robotics and Dynamics (RaD) Lab under the direction of Marc Killpack. Before joining the lab, I was required to have a certain skill level in Python, Linux, and other third party robotics software libraries. To compensate for my lack of knowledge in these areas, I spent 30 hours in a single semester outside of class and work completing tutorials and developing these necessary skills. As a result, I was able to join the lab and gain valuable research experience. This demonstrates my drive to succeed and ability to overcome obstacles in my path, both valuable skills that will continue to benefit me as a researcher.

At the RaD Lab, we work with pneumatically actuated soft robots. These soft robots are inherently safer around humans than traditional robots and have significant space technology applicability (weighing an order of magnitude less than Robonaut 2). I led a team of three other undergraduate students to develop a fabric tactile sensor that wrapped around the soft robots to provide force feedback for control implementation. I wrote both the microcontroller code to collect data from the sensor and the Python code to implement the sensor with the robots in the lab. This sensor has been effectively implemented as feedback for a soft robot force controller. Now, these robots will be able to operate even more safely around humans (e.g. performing astronaut assistance tasks in the International Space Station or equipment maintenance on Mars).

1.1.3 The Aerospace Corporation - 2016

This past summer, I worked at a second federally funded research and development center, The Aerospace Corporation. While there, I worked primarily on three projects. First, I designed, built, and calibrated a testing setup to successfully measure the thrust generation of a new type of UAV in Martian atmosphere. This included selecting vacuum compatible load cells, designing the mounting hardware, and writing the LabVIEW code to collect the data. Second, I was responsible for determining the heat transfer rate of new thermoelectric cooling modules. The Aerospace Corporation was researching these modules as a potential replacement for cryocoolers on satellites. I designed a test plan and wrote a thermal PID controller in LabVIEW that regulated the temperature difference across the module. My LabVIEW code completely automated the data collection which saved weeks of engineering time. To tune the PID controller, I performed system identification to create a first order model and simulated its response in Simulink. During my last project, I wrote a gradient based optimization in MATLAB to orient six accelerometers on a reaction wheel jitter test stand.

This internship reinforced my love of working in a research based environment. I want the algorithms I develop during my graduate research to influence the lives of real people. This means that they will need to be implemented on real hardware. This experience in working with control system design on real hardware and writing an optimization for real data has been invaluable in preparing me for graduate research in controls and robotics.

1.2 Space Technology Research, and Career Goals

Through my internships at LANL and The Aerospace Corporation, I learned that participating in cutting edge research and obtaining a graduate degree will greatly enhance my ability to benefit society. I fully intend to participate in similar research activities throughout my career. In fact, my work at The Aerospace Corporation was received well enough that I have the opportunity of returning to work there after the completion of my degree to contribute to the nation's scientific understanding of space dynamics and control.

1.3 How My Proposed Course of Study and Research will Help Me Achieve These Goals

I am pursuing my graduate degree in the RaD Lab at BYU where I will research multi-arm manipulation with soft, pneumatically actuated robots. As a part of this research, I will develop advanced dynamic models, write and implement controllers, and work with a variety of robots. This experience of solving open ended problems will be priceless in my future career. I will also have the opportunity to present my research at multiple conferences and collaborate with other researchers in my field. My graduate degree will enable me to work shoulder-to-shoulder with other experts to address some of the nation's most difficult challenges.

2 <u>Project Narrative</u>

2.1 Introduction and Motivation

Robots revolutionized the manufacturing industry 30 years ago, but human-robot interaction is still in its infancy. Imagine a robot that could gently help a disabled person into their wheelchair, lift a survivor to safety in a disaster scenario after carefully digging through rubble, or even work alongside an astronaut in space. Industrial robots, though highly precise and capable, have a relatively high inertia. This severely limits how quickly and safely they can move to avoid unexpected collisions and high impact forces while operating in close proximity to humans.[2] Current robots for space missions, like Robonaut 2, mainly rely on rigid links with compliant joints. One of the purposes of Robonaut 2 is to provide performance data on how a robot works side-by-side with astronauts.[3] Despite having compliance at the joints, Robonaut 2 still has relatively high inertia which limits how quickly it can move around delicate equipment or human collaborators. The footprint and weight of robots used in space are also critically important, and the current robots used are comparatively large and heavy. My research will focus on inflatable, pneumatically actuated (soft) robots–like the one in *Figure 1*–which will use comparatively less payload, weighing an order of magnitude less than Robonaut 2 and occupying significantly less volume when deflated. Because these robots have soft links with low inertia, they are *inherently* safer around people and equipment even when moving at higher speeds than traditional space robotics. In short, development of soft robotics has significant merit in space technology and human-robot interaction.

Figure 1: Five degree of freedom soft robot developed by Pneubotics

One important feature in robots capable of working around humans or mimicking human dexterity is the ability to use two or more arms. Many tasks such as lifting heavy/bulky objects or service and assembly tasks are difficult or even impossible with only one arm. Furthermore, because soft robots are so lightweight, it's possible that a single robot may not have the capacity for tasks requiring high force. In these situations, it makes sense to have multiple lighter robots in space for redundancy and to collaborate in manipulating heavier things. These challenges have sparked a large amount of research into multi-arm manipulation. My research will focused on coordinated, multi-arm manipulation using inflatable, pneumatically actuated (soft) robots like the one in *Figure 1.*

2.2 Background

Multi-arm manipulation does not have a specific agreed-upon definition. It could be many fingers on a hand manipulating a small object, or many arms manipulating a large object. In fact, both of these scenarios could use the same control principles. Furthermore, multi-arm manipulation can be categorized by un-coordinated and coordinated tasks. Un-coordinated manipulation tasks are those in which the arms are performing tasks that do not require interaction (e.g. one arm is moving parts while a second arm is performing an unrelated assembly task). Jobs which require two or more robotic arms to physically interact with the same object are classified as coordinated manipulation tasks.[4] My research will be focused on coordinated, multi-arm manipulation tasks.

One difficulty in coordinated, multi-arm manipulation with traditional robots is that small deviations in end effector position or orientation from any of the arms while holding a rigid object can result in large stresses on both the object and internally on the arm. To compensate, many researchers have proposed hybrid force/position control schemes which seek to control the position of an object being grasped by several manipulators while either keeping the forces below a certain threshold or maintaining a certain force.[5, 6, 7, 8, 9] A challenge with this approach is the coordination of high bandwidth centralized controllers. Additionally, if the software or hardware malfunctions and the force control stops working, traditional robots could exert a dangerous amount of force on the object being manipulated, themselves, humans, or other delicate equipment nearby.

An alternative and novel approach is to mitigate buildup of high forces by using a robot with flexible links and passive compliance in the joints from the compressibility of air. Because soft robots are inherently compliant, deviations in object position result in significantly lower buildup of forces; thus, they lend themselves nicely to tasks involving several arms. Even tasks with one rigid arm and multiple soft arms become simpler as the whole system is forgiving of end effector deviations due to compliance of the soft arms. Therefore, one of the major concerns with successful implementation of coordinated, multi-arm manipulation is eliminated. Additionally, because these robots are soft and inherently compliant, they are very safe around humans and delicate equipment even if something malfunctions. On the other hand, compliant links and joints introduce new challenges (addressed below) into the control paradigm, and currently do not perform as well as state of the art torque controlled robots like Robonaut 2.

2.3 Hypothesis

I propose that coordinated multi-arm manipulation can realistically be implemented with inflatable, pneumatically actuated robots. My goals are to implement coordinated multi-arm control for (1) impact tasks with rigid objects (like sweeping off a solar panel or assembly of construction materials that require impact for insertion) and (2) soft object manipulation tasks (like moving a tarp or a flexible solar array). Here are the underlying questions to address:

- Two key challenges with soft robots are accuracy and repeatability. The dynamics of the arms can change with a variety of different stimuli such as temperature change (which can be drastic in space), pressure loss through bladder punctures, and actuation hysteresis. Additionally, the bladders often reseat themselves as the arms move. What type of control scheme will result in the highest task space accuracy and repeatability?
- There are many different types of control schemes for coordinated multi-arm manipulation presented in the literature. Which type of control scheme will be most effective in coordinated manipulation tasks for soft robots?
- Some tasks require more stiffness than is nominally available in a single soft robot arm. I propose that such tasks could become more feasible by grasping one arm with the other (increasing the rigidity by forming a closed kinematic chain). This type of task would not be feasible with a rigid robot. How will the control scheme need to be altered to accurately control this system?

To answer these research questions, there are many intermediate steps described in the following section.

2.4 Research Plan

Manipulability Improvement: After spending the last year in the RaD Lab, I am familiar with the challenges of accurately controlling soft robots. Recent design changes have left the robot in *Figure 1* with only four degrees of freedom per arm. To perform general multi-arm manipulation tasks, each end effector needs to be controllable in at least six degrees of freedom. I will work with undergraduate students to help add at least two additional degrees of freedom per arm to improve manipulability. Another student in my research group recently submitted a paper to ICRA 2017 on rigorous design optimization of soft robots. I will build on this work in selecting which degrees of freedom to add and how they should be mounted.

Single Arm Hybrid Controller Development: Task space accuracy and repeatability are affected by dynamic and kinematic model error (accurately modeling the robot in *Figure 1* and other soft robots is not trivial). Previous researchers in the RaD Lab have designed an algorithm using model predictive control (MPC) that can command a single arm in joint space.[10] I will use inverse kinematics libraries – like TRAC-IK in the Robot Operating System–to compute desired joint angles for this controller; however, this control method alone will not result in accurate task space positions and orientations due to dynamic and kinematic error. A common control technique to close error is visual servoing.[11, 12] My first approach to this problem will be to create a hybrid controller using the RaD Lab's high-precision motion capture system for servoing to close the position error and improve repeatability. A more mobile solution will incorporate an HTC Vive virtual reality system with sub millimeter tracking accuracy. This system tracks targets which, when attached to the end effectors, should provide task space position/orientation feedback. This controller will be of the form:

$$q_{cmd} = q_{des} + \Delta q$$
$$q_{des} = IK([x_{des} \quad y_{des} \quad z_{des} \quad \theta_{des} \quad \phi_{des} \quad \psi_{des}]^T)$$

Δq is the result of an optimization defined by:

$$\begin{aligned} &\text{minimize:} && \|\Delta x - J\Delta q\| \\ &\text{subject to:} && \textit{Joint Limit Constraints} \end{aligned}$$

Where q_{des} is the original joint angle commands (from inverse kinematics) sent to the MPC controller, q_{cmd} is the joint angle commands updated by Δq which is the change in the joint angle commands, x_{des}, y_{des}, and z_{des} are the desired end effector position in Cartesian space, θ_{des}, ϕ_{des}, and ψ_{des} are Euler angles describing the end effector orientation, Δx is the task space position and orientation error, and J is the Jacobian. It should be noted that the objective function for the optimization relies on an approximation which is only valid for small Δx and Δq.

Coordinated, Multi-Arm Controller Development: My first approach at coordinated multi-arm manipulation will be to design and implement an object level model predictive controller. This approach uses a forward model of the object dynamics to predict the effects of control inputs over a short time horizon. In this case, the control inputs are forces and torques applied to the object by each manipulator (see *Figure 2*). It then selects the optimal inputs for that horizon to achieve the desired object motion. Another student in my research group has researched estimating the dynamics of an unknown object. I will build on this research to estimate dynamic models for the various objects I will manipulate. These models will likely have error, but previous research with MPC has found it

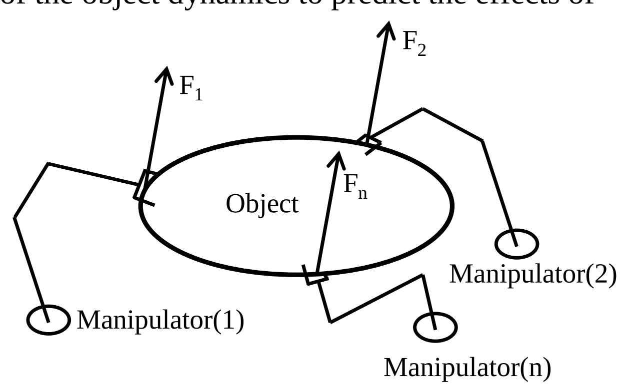

Figure 2: Manipulators exerting forces on an object

to be robust to modeling error (even with plus or minus half of nominal mass values).[13, 14] My proposed control scheme is of the form shown in *Figure 3*.

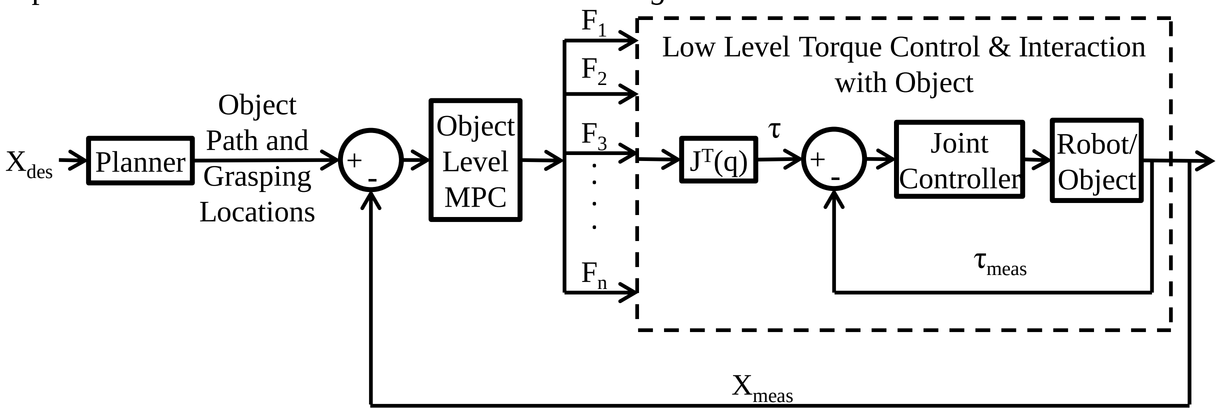

Figure 3: Proposed object level control scheme

X_{des} and X_{meas} are desired and measured end effector position and orientation, F_1 to F_n are wrenches at the end effector of each arm which are fed into a low level joint torque controller, J is the Jacobian of each arm, and τ and τ_{meas} are the required and measured joint torques.

One of the first steps in designing this controller will be to develop a path planner which will have two main objectives. First, it will output an optimal object path which avoids obstacles when given a desired object position and orientation. This path must be constrained to object motion that is possible given the force/torque constraints of the robot manipulators. A student in the RaD lab has already worked extensively on this problem for a single arm, and I will build on his work. Second, the path planner will determine the optimal location on the object for each arm to grip in order to maximize the force manipulability ellipsoid over the course of the path. Maximizing the force manipulability ellipsoid will enable each arm to better compensate for disturbances/deviations over the course of the path. I took a graduate optimization course during my bachelor's degree which will help me to formulate and solve this optimization problem.

Once I can accurately and repeatably manipulate objects using the two arms on the robot in *Figure 1*, I will expand my research to utilize more soft arms and even a more traditional torque controlled Baxter Research Robot Arm. This will demonstrate the applicability of my algorithms to systems that include multiple soft robots and a rigid robot.

Closed Kinematic Chain Modeling: To address my last research question, I will begin by modeling the gripping of one arm by the other as a closed kinematic chain. Previous students in my research group successfully implemented simultaneous joint angle and stiffness control for an inflatable robot.[15, 16] I will build upon this research by developing a controller for the closed kinematic chain with two additional tuning parameters (the stiffness of the gripping arm and the gripping location) which can be optimized for a given task.

2.5 Choice of Academic Institution

I chose to pursue this research in the RaD Lab at BYU for many reasons. As part of a NASA Early Career Faculty Space Technology Research (ECF) Grant, the RaD Lab has a unique availability of compliant robot arms (four arms from two Baxter robots and six pneumatically actuated soft robot arms). Because of this, BYU is ideally positioned for me to work on this kind of problem. With less time and money spent procuring and setting up hardware, I can focus my efforts on developing useful dynamic models and control algorithms. Additionally, other researchers in the RaD Lab have made significant progress with robots in the lab which provides a foundation for my research. Finally, the RaD Lab has the expectation that every graduate student will publish a *minimum* of two conference papers and a journal paper. This expectation ensures that I will disseminate my results so that other researchers in the field can build on my progress.

2.6 Application to the NASA Technology Roadmaps

TA 4.3.5: Collaborative Manipulation states, “For collaborative manipulation, the required technical capability is to provide a teamed approach for multiple robots or teams of humans and robots working with objects, equipment, or samples.” This collaboration includes coordinated manipulation tasks, where multiple robot manipulators are physically connected together in tasks like handling a common load. My graduate research directly impacts these goals. I will be researching and implementing control methods for coordinated multi-arm manipulation tasks with soft, pneumatically actuated robots. Furthermore, TA 4.3.5 lists robust safety system development as a goal. TA 4.7.5: Safety and Trust expands on this by setting the goal of having a crew “be able to work next to a robotic assistant, within a one-meter proximity in a controlled and safe manner, without being physically attached to it.” The soft robotic platforms I will be using for my research are *inherently* safe for operation around humans and delicate equipment due to their inflatable structure and low inertia. The algorithms I develop will help these robots have performance on par with humans (for some tasks).

More generally, the sub-goal listed in TA 4.3: Manipulation is to “Increase Manipulator dexterity and reactivity to external forces and conditions while reducing overall mass and launch volume and increasing power efficiency.” Providing structures developed from lightweight materials for robotic arm design is listed as a goal of TA 4.3.1.2: Lightweight Structures.[17] The soft robots I will be researching are not only an order of magnitude lighter than current space robotic technology like Robonaut 2, but also occupy 10 times less volume when deflated. My research on control algorithms for multi-arm manipulation will contribute to making lightweight, inflatable robotic arms beneficial in space applications. A single soft robot may not have the power output of heavily-geared industrial robots or even more recent torque-controlled robots, but soft robots have such a low weight and volume that it would still drastically reduce the overall launch payload to send multiple soft robots on space missions. My research will make this feasible by enabling multiple soft robots to collaborate with each other on the same task.

2.7 Impact of Visiting Technologist Experience

I chose to pursue graduate research largely because I want to create technology that is truly capable of changing the world. Coordinated multi-arm manipulation with soft robots has many space applications as mentioned above, and I view the visiting technologist experience as an opportunity to collaborate with subject matter experts in integrating this promising technology in space specific applications. Furthermore, this will be an opportunity to disseminate my research results within the NASA technical community. The research knowledge and skills I develop during the visiting technologist experience will also greatly benefit the research I will be completing at BYU.

My career ambition is to be involved in space technology research and development. This collaboration with NASA scientists would both introduce me to the research culture of NASA and help me become more familiar with current cutting edge space technology developments. An understanding of the current developments and needs of an industry is critical in performing contributing research. In short, this would be an invaluable experience for my career goal of performing research critical to our nation’s space industry, and I know that my graduate research can have a broad impact on robotic manipulation for future space missions.

2.8 References

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[11] Wang, H., Yang, B., Liu, Y., Chen, W., Liang, X., & Pfeifer, R. Visual Servoing of Soft Robot Manipulator in Constrained Environments with an Adaptive Controller. IEEE/ASME Transactions on Mechatronics.

[12] Vahrenkamp, N., Böge, C., Welke, K., Asfour, T., Walter, J., & Dillmann, R. (2009, December). Visual servoing for dual arm motions on a humanoid robot. In 2009 9th IEEE-RAS International Conference on Humanoid Robots (pp. 208-214). IEEE.

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3 Degree Program Schedule

Enter Master's Program	August 2016
Submit Program of Study	November 2016
Submit Prospectus	January 2017
Submit conference paper to the International Conference on Intelligent Robots and Systems 2017 (IROS 2017)	March 2017
Submit conference paper to The International Conference on Robotics and Automation 2018 (ICRA 2018)	September 2017
Present at IROS 2017 (Vancouver, Canada)	September 2017
Submit to robotics journals	March 2018
Present at ICRA 2018 (Brisbane, Australia)	May 2018
Visiting Technologist Experience with NASA	May – July 2018
Thesis Defense and Graduation	August 2018

4 CV (see pages 10-11)

5 Transcript (see pages 12-15)

6 GRE Scores (see pages 16-17)

Dustan Kraus

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EDUCATION

Brigham Young University | *Mechanical Engineering* Provo, UT | Aug. 2009 – Present

- Bachelor's Degree in Mechanical Engineering:
    - Graduated Cum Laude in April 2016
    - GPA: 3.89/4.00
- Master's Degree in Mechanical Engineering:
    - Emphasis in controls and robotics
    - Enrolled: August 2016
    - Expected graduation: August 2018
- Relevant Coursework/Research:
    - *Design of Control Systems*: Used the Euler Lagrange equation to develop equations of motion, transfer functions, and state space design models for a 2 rotor helicopter. Designed and tuned the gains for PID and observer based controllers using simulations in MATLAB, Simulink, and LabVIEW. Implemented the controllers onto the actual hardware, and successfully controlled the helicopter.
    - *Flight Controls and Dynamics:* Used MATLAB and Simulink to develop an autopilot/controller and flight simulator for a UAV drone. This included implementing algorithms for trajectory following and path planning. Simulated real sensor data, and implemented an Extended Kalman Filter for state estimation.
    - *Programming Experience*: C++, MATLAB, Python, Simulink simulation modeling, LabVIEW
    - *Tactile Sensor Development*: Using Linux, an Arduino, python, and ROS to develop and implement tactile sensing onto a soft, pneumatically actuated robot arm

PROFESSIONAL AND VOLUNTEER EXPERIENCE

The Aerospace Corporation | *Electromechanical Controls Intern* El Segundo, CA May – Aug. 2016

- Designed and built a fixture for testing accelerometer alignment of a reaction wheel jitter characterization test setup on a shaker table
    - Collected accelerometer data with LabVIEW, filtered the data, and wrote a gradient based optimization in MATLAB that successfully found the rotation matrices to align the accelerometers
- Designed an experiment to determine the heat transfer capabilities of a thermoelectric cooling module designed to replace cryocoolers on satellites
    - Automated testing by developing a first order dynamic model and writing a PID controller in LabVIEW to control the temperature gradient
- Designed, built, and calibrated a testing setup to measure thrust generation of a novel UAV in Martian atmosphere
    - Included selecting vacuum compatible load cells, designing the mounting hardware, and writing LabVIEW code to collect data
    - Successfully collected thrust data in a large vacuum chamber

Brigham Young University | *Robotics Research Assistant* Provo, UT
Aug. 2015 – Present

- Led a team of three other undergraduates to develop a fabric tactile sensor to provide force feedback for control implementation on soft, pneumatically actuated robots
- Wrote both the microcontroller code to collect data from the sensor and the Python code to implement the sensor with the robots in the lab
- This sensor has been effectively implemented as feedback for a soft robot force controller enabling soft robots to operate even more safely around humans and delicate equipment

Los Alamos National Laboratory | *Research Fellowship* Los Alamos, NM
June – Aug. 2014

- Created a novel multimodal sensing system capable of detecting and identifying transparent barriers while reporting distance and angle of approach to these barriers onboard a mobile platform (quadrotor drone)
- Worked in a multidisciplinary team to design and build a prototype of this system
- Demonstrated accuracy, speed of response, and functionality of the completed prototype
- Developed technical communication skills by preparing a conference paper and presentation on my group's research; personally presented our results at the 2015 SPIE Conference

The Church of Jesus Christ of Latter-day Saints | *Volunteer Missionary* Jamaica
June 2010 – 2012

- Spent from 10 a.m. to 9 p.m. each day doing the following:
  - Teaching, building houses, constructing chicken coops, clearing farmland, and performing other acts of humanitarian service
  - Developed leadership by preparing and teaching lessons to 55 other missionaries throughout the island about how to be more efficient

PUBLICATIONS AND TECHNICAL PRESENTATIONS

- Conference Paper:
  - Acevedo, I., Kleine, R. K., Kraus, D., & Mascareñas, D. (2015, April). Multimodal sensing strategies for detecting transparent barriers indoors from a mobile platform. In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring (pp. 94310V-94310V). International Society for Optics and Photonics.
- Presentation:
  - Title: Multimodal Sensing Strategies for Detecting Transparent Barriers Indoors from a Mobile Platform
  - Date: March 10, 2015
  - Type: Oral presentation with PowerPoint
  - Conference: SPIE 9431, Active and Passive Smart Structures and Integrated Systems 2015

AWARDS

- Developed leadership by becoming an Eagle Scout
- Tuition for 5 years of college paid for by academic scholarships, including:
  - BYU Heritage Scholarship – 4 years full tuition
  - Sallie Mae Bank Scholarship – 1 year full tuition

```
     STUDENT INFORMATION
    NAME                :  Kraus, Dustan Paul
    BYU ID              :  14-080-1599
    BIRTHDATE           :  [redacted]
    GENDER              :  Male

    DEPARTMENT          :  Mechanical Engineering
    MASTERS MAJOR       :  Mechanical Engineering
--------------------------------------------------------------
DEGREES AWARDED - BRIGHAM YOUNG UNIVERSITY
  DEGREE                :  BS
    DATE RECEIVED       :  Apr 2016
    DEPARTMENT          :  Mechanical Engineering
    MAJOR               :  Mechanical Engineering
    HONORS              :  Cum Laude
--------------------------------------------------------------
BYU COURSE WORK
  TEACH CRS   SEC   H     COURSE DESCRIPTION                SEM   GRD
  AREA  NO.   NO.                                           HRS



Fall Semester 2009
  HIST  201   015         World Civilization to 1500        3.00  A-
  BIO   100   002         Principles of Biology             3.00  A-
  EXSC  191   013         Weight Training, Beginning        0.50  A     RPT
  MATH  113   008         Calculus 2                        4.00  A-
  REL A 121   052         The Book of Mormon                2.00  B
  REL C 130   003         Missionary Preparation            2.00  A

 SEM HR ERN  14.00  HR GRD   14.00  GPA  3.64



Winter Semester 2010
  EC EN 191   001         New Student Seminar               0.50  P
  C S   142   002         Intro to Computer Programming     3.00  W
  CHEM  105   030         General College Chemistry         4.00  A
  EXSC  121   001         Diving, Springboard               0.50  P
  EXSC  162   001         Skiing, Intermediate              0.50  P
  EXSC  191   018         Weight Training, Beginning        0.50  P
  MUSIC 101   001         Introduction to Music             3.00  A-
  PHSCS 121   002         Principles of Physics 1           3.00  A
  REL A 122   029         The Book of Mormon                2.00  A-
 SEM HR ERN  14.00  HR GRD   12.00  GPA  3.88



Fall Semester 2012
  CE EN 103   004         Engineering Mechanics-Statics     3.00  A
  HIST  202   003         World Civilization from 1500      3.00  B+
  ME EN 172   001         Eng Graphics                      3.00  A
  ME EN 191   001         New Student Seminar               0.50  P
  REL A 212   003         The New Testament                 2.00  A
  WRTG  150   045         Writing & Rhetoric                3.00  A
 SEM HR ERN  14.50  HR GRD   14.00  GPA  3.87
```

Winter Semester 2013

A HTG 100	036	American Heritage	3.00	A
CE EN 203	002	Engr Mechanics - Materials	3.00	A
DANCE 180	007	Social Dance, Beginning	0.50	A
ENG T 231	001	Foundations Global Leadership	3.00	A
MATH 313	002	Elementary Linear Algebra	3.00	A
PHSCS 123	001	Principles of Physics 2	3.00	A

SEM HR ERN 15.50 HR GRD 15.50 GPA 4.00

Fall Semester 2013

CE EN 204	001	Engr Mechanics - Dynamics	3.00	A
MATH 314	002	Calculus of Several Variables	3.00	B+
ME EN 250	002	Materials Science	3.00	A-
PHIL 110	003	Introduction to Philosophy	3.00	A
PHSCS 220	001	Intro Electricity & Magnetism	3.00	A

SEM HR ERN 15.00 HR GRD 15.00 GPA 3.82

Winter Semester 2014

EC EN 301	001	Elements of Electrical Engr	3.00	A
MATH 334	001	Ordinary Differential Equation	3.00	A
ME EN 282	004	Manufacturing Processes	3.00	B+
ME EN 321	001	Thermodynamics	3.00	A
REL C 234	002	LDS Marriage & Family	2.00	A

SEM HR ERN 14.00 HR GRD 14.00 GPA 3.87

Fall Semester 2014

ENGL 316	005	Technical Communication	3.00	A
ME EN 363	001	Elementary Instrumentation	3.00	A
ME EN 372	001	Mechanical Sys Dsgn Fundmntls	3.00	A-
ME EN 373	003	Intro to Sci Computing & CAE	3.00	A
REL C 325	014	The Doctrine & Covenants	2.00	A

SEM HR ERN 14.00 HR GRD 14.00 GPA 3.94

Winter Semester 2015

ME EN 312	002	Fluid Mechanics	3.00	A
ME EN 335	001	Dynamic System Modeling	3.00	A
ME EN 585	001	Manufg Competitiveness	3.00	A
REL C 324	004	The Doctrine & Covenants	2.00	A
STAC 110	016	Indoor Cycling	0.50	P
STAT 201	001	Stat for Engineers & Scientist	3.00	A

SEM HR ERN 14.50 HR GRD 14.00 GPA 4.00

Fall Semester 2015

ME EN 431	001	Design of Control Systems	4.00	A
ME EN 475	001	Integrated Prodct&Proc Desgn 1	3.00	A-
ME EN 497R	017	Mentored Projects	3.00	A
ME EN 552	001	Neuromechanics of Movement	3.00	A

SEM HR ERN 13.00 HR GRD 13.00 GPA 3.93

Winter Semester 2016

ME EN 340	001	Heat Transfer	3.00	A
ME EN 476	001	Integrated Prod&Proc Dsgn 2	3.00	A
ME EN 575	001	Optimization Techniques	3.00	A
ME EN 634	001	Flight Dynamics & Control	3.00	A

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  STAC  109   003         Yoga                            0.50  W
  STAC  191   018         Weight Training, Beginning      0.50  P
 SEM HR ERN  12.50  HR GRD   12.00  GPA  4.00

ENTRANCE EXAMS
    ACT          12/2007  COMP 27
    ACT          04/2008  COMP 32
    ACT          06/2008  COMP 33
    ACT          09/2008  COMP 32
    GRE          10/2015  COMP 328.0
    SAT1         05/2008  COMP 1290

--------------------------------------------------------------
CURRENT ENROLLMENT



Fall Semester 2016
  EC EN 671   001         Math of Signals & Systems       3.00
  ME EN 537   001         Adv Mechanisms, Robotics        3.00

--------------------------------------------------------------
FUTURE ENROLLMENT



Winter Semester 2017
  ME EN 534   001         Dynamics of Mech Systems        3.00
  ME EN 733   001         Linear System Theory            3.00

--------------------------------------------------------------
BYU GPA SUMMARY


 BYU HR ERN 141.00  HR GRD  137.50  GPA  3.89
--------------------------------------------------------------

TRANSFER CREDITS ACCEPTED

ADVANCED PLACEMENT


 CHEMISTRY                          25    Score = 3
  AP    100R             AP Credit                        3.00  P
  CHEM  101              Introductory General Chemistry   3.00  P


 EUROPEAN HISTORY                   43    Score = 3
  AP    100R             AP Credit                        6.00  P


 MATH - CALCULUS AB                 66    Score = 5
  MATH  112              Calculus 1                       4.00  P
  MATH  110              College Algebra                  3.00  P


 PHYSICS B                          78    Score = 5
  PHSCS 105              Intro Applied Phys               3.00  P
  PHSCS 106              Intro Applied Phys               3.00  P


 PSYCHOLOGY                         85    Score = 5
  PSYCH 111              General Psychology               3.00  P


 STATISTICS                         90    Score = 5
```

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 STAT  221               Principles of Statistics         3.00  P
AP  HR ERN  31.00  HR GRD    0.00


TRN HR ERN  31.00  HR GRD    0.00
--------------------------------------------------------------


TOT HR ERN 172.00  HR GRD  137.50  HR ATT  176.00  GPA  3.89
```

ETS GRE

Examinee Score Report

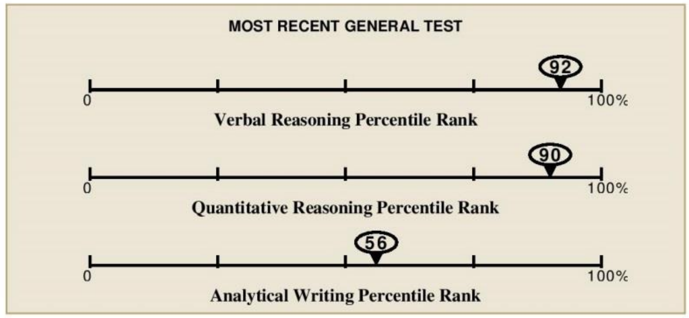
Note: This report is not valid for transmission of scores to an institution.

Kraus, Dustan

Last (Family/Surname) Name, First (Given) Name, Middle Initial

Print Date: 10/16/2015

Address:	488 South 450 East Provo, UT 84606
Email Address:	dustan.kraus@gmail.com
Phone Number:	2085400284
Date of Birth:	[redacted]
Social Security Number (last 4 digits):	2676
Gender:	Male
Intended Graduate Major Code:	1502
Intended Graduate Major:	Engineering -- Mechanical - Mechanical Engineering
Most Recent Test Date:	10/08/2015
Registration Number:	4494056



All dates are formatted as MM/DD/YYYY.

This score report includes all of your General Test and Subject Test scores earned from July 1, 2008 to the present. Only reported scores are available for display.

General Test Scores

Test Date	Verbal Reasoning*				Quantitative Reasoning*				Analytical Writing	
MM/DD/YYYY	Prior Format		Current Format		Prior Format		Current Format			
	Scaled Score	Estimated Current Score	Scaled Score	% Below	Scaled Score	Estimated Current Score	Scaled Score	% Below	Score	% Below
10/08/2015			163	92			165	90	4.0	56

NS - No Score. Indicates that no questions were answered.
* The GRE Verbal Reasoning and Quantitative Reasoning score scales changed in August 2011. For tests taken August 2011 or later, scores are printed in the "Current Format" columns. For tests taken before August 2011, scores on the prior scales and the corresponding estimated scores on the current scales are printed in the "Prior Format" columns.

Subject Test Scores

Test Date	Test Name / Subscore Name	Scaled Score	% Below

Score Recipient(s)

Your score reporting history is shown below. "Pending" indicates your scores are not yet available, or your order has not yet been processed.

Undergraduate Institution				
Report Date	**Institution (Code)**	**Department (Code)**	**Test Type**	**Test Date**
10/16/2015	Brigham Young U (4019)	Mechanical Engineering (1502)	General Test	10/08/2015

Score Recipient(s)				
Report Date	**Institution or Fellowship Sponsor (Code)**	**Department (Code)**	**Test Type**	**Test Date**
10/16/2015	Stanford U (4704)	Mechanical Engineering (1502)	General Test	10/08/2015
10/16/2015	MIT (3514)	Mechanical Engineering (1502)	General Test	10/08/2015
10/16/2015	Brigham Young U (4019)	Mechanical Engineering (1502)	General Test	10/08/2015
10/16/2015	U CA Berkeley (4833)	Mechanical Engineering (1502)	General Test	10/08/2015

* Undergraduate Institution does not wish to receive scores
** Score recipient not valid/active

QUESTIONS ABOUT THIS GRE EXAMINEE SCORE REPORT

Information to help you interpret your GRE scores is available at www.ets.org/gre/stupubs. If you have any questions concerning this GRE Report of Scores, call ETS at 1-609-771-7679 or 1-866-473-4373 (toll free for test takers in the U.S., U.S. Territories*, and Canada) between 8:00 a.m. and 7:45 p.m. EST or email gre-info@ets.org. For information about interpreting your scores, consult **Interpreting Your GRE Scores**, which is available at www.ets.org/gre/understand.
**Includes American Samoa, Guam, Puerto Rico, and U.S. Virgin Islands*

SCORE REPORTING

Policies pertaining to score reporting and use are periodically reviewed and revised by the GRE Board. The policies and procedures explained in the 2013-14 *GRE Information and Registration Bulletin* are effective only for the time period of August 1, 2013 to June 30, 2014 and supersede previous policies and procedures in previous bulletins. GRE scores are reportable for five(5) years following the testing year (July 1 to June 30) in which you tested. Currently, GRE scores earned after July 1, 2008 are available.

PERCENTILE RANK (% BELOW)

The percentile ranks in this report indicate the percentage of examinees who scored below your score. Note that these percentile ranks may be different from those that applied when the scores were originally reported to you if the scores were earned prior to July 2013. This reflects annual updating of these data to permit admissions officers to compare scores, whenever earned, with those for a recent reference group.

RETAKING A GRE TEST

You can take the GRE revised General Test once every 21 days, and up to five times within any continuous rolling 12-month period. This applies even if you canceled your scores on a test taken previously. You may take the paper-based GRE revised General Test and GRE Subject Tests as often as they are offered.
Note: This policy will be enforced even if a violation is not immediately identified (e.g., inconsistent registration information) and test scores have been reported. In such cases, the invalid scores will be canceled and score recipients will be notified of the cancelation. Test fees will be forfeited.

SCORES NOT REPORTED

"Scores Not Reported" is listed in the Report Date column of the Score Recipients section of your score report if one of three scenarios occurs:

- You requested scores to be sent to an undergraduate institution that does not receive scores.
- The code for the graduate institution you designated to receive scores is no longer active.
- Your reportable score record does not include scores for the requested test.

Note: *This report is not valid for transmission of scores to an institution.*