Columbia University
Department of Mechanical Engineering
Senior Design
MECE E3420
Fall 2014

Literature Review

Delta Force

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1. Introduction

For our senior design project, we decided to create a delta robot. Through our literature search, we found that the basic principles of delta robots have been thoroughly explored, and many of the associated fundamental equations have effectively been solved. However, the optimization of delta robots is still a very active field. The main specifications of a delta robot are (i) speed of operation, (ii) precision, (iii) maximum load, (iv) range of motion or workspace, and (v) cost. It is relatively straightforward to create a delta robot that maximizes one of these conditions, but it is effectively impossible to create one maximizing all of them. For example, a robot capable of carrying loads in excess 50 pounds will necessarily be slow to accelerate, due to Newton's Laws (F=ma). Thus, every delta robot is a compromise; the designer must find the appropriate combination of these five specifications for whichever use the robot will be applied to.

Our internet search revealed that in general, the delta robot community is split into two major spheres. Firstly, there is the industrial delta robot sphere. A few midsize companies produce delta robots for use in assembly line applications, 3D printing applications, and more. Many of these industrial robots push the limits of speed, strength, and precision, but they can be extraordinarily expensive and are usually quite large. Furthermore, as these robots are sold openly on the market, they are usually designed as generalized delta robots that can be used in a range of processes. As such, they may not be ideally optimized to any single specific purpose. The other sphere of the community is made up of a large number of very dedicated hobbyists who build their own personal delta robots for whichever purpose interests them. Recently, many of these personal delta robots have been focused on 3D printing. There is an incredible variety of designs spanning an extraordinary budget range among these hobbyists. On Youtube, there are videos of casual hobbyist basic delta robots made plywood of wood and Styrofoam, as well as videos of hardcore hobbyists who make advanced robots using professional grade equipment.

Through our journal search, we found that most academic work on delta robots today focuses on developing new techniques, materials, and processes that will enable delta robots to achieve several of the five conditions to a high degree. There is academic research into using new materials with delta robots in order to limit weight without sacrificing strength, developing new software to optimize the motion of delta robots, and much more.

During our patent search, we found hundreds of examples of patent applications for delta robots that had been optimized to specific applications. Many of these patents added additional components to the delta robot itself, including additional sensors for more precise control under certain conditions and counterweights to maintain the robot's center of balance during motion. Other patents were focused on designing and implementing specific unique end effectors including motors and medical devices. Still others altered the basic shape of the delta robot, using additional arms to access an additional degree of freedom or using a unique system to drive the parallel linkages.

After performing our search, it is clear that we should aim to create a delta robot towards a specific purpose, ideally one that has not been explored much. We should then optimize the geometry, motors, encoders, control system, and end effector of the robot in order to best achieve that purpose while remaining within our budget. In order to find uses for delta robots that have not already been explored, we are in the process of reaching out to graduate students and professors at Columbia University, and asking about the research going on in their labs. Two potential options we have already found are a medical robot for Hirobumi Watanabe, a post-doctoral researcher in Professor Kysar's lab, or a robot to direct a fibre laser for use in Professor Yao's advanced manufacturing laboratory. In addition to optimizing our robot for an unexplored purpose, we also hope to create some "fun" applications that we will be able to demonstrate at the expo, as our technical medical/laser based applications may not be too exciting to watch. These fun applications will be based on the same frame and structure, but will simply use different end effectors. Thus, our robot must include a generalized head with clips to apply different end effectors for different purposes. Some of the alternative applications could include a drawing tool capable of drawing a picture from a vectorized image, and a pick and place robot that could play chess or a simpler game.

2. Internet Search

Our internet search revealed the wide range of applications for delta robots. One of the most helpful sites is one called RepRap.com, which is a "wiki" style webpage with an abundance of information on delta and parallel robots [1] It features hardware, software, and calibration advice for hobbyists and tinkerers and is therefore very easy to follow and the articles are written in a straightforward fashion. There are YouTube videos about the robot build, links to GitHub code, and full instructions for how to build a simple delta robot. It features a comprehensive parts lists including the types of motors used, timing belt, bearing, specs and more. Basically if you followed the instructions and bought all of the parts, you would have a full working delta robot printer for weekend or two's worth of work. The useful parts of this internet search include the motor, power supply, and controller details. By looking at how this build is made, we can modify and expand on the work they have already done. The links to the github code leads to the program that many people use to control the robots for 3-D printing applications. We plan on dissecting this code and seeing if we can use or modify some of the functions.

Another comprehensive online resource is a website called www.parallemic.com which stands for the Parallel Mechanism Information Center. [2] This website is also a hub, which offers guides to building the mechanisms, the software needed to drive the motors, as well as links to other informational guides. An interesting part of this website is that they have a "who's who" in parallel robotics and list research labs and companies that are doing R&D in the field. It also features a patent list with hundreds of patents related to delta and parallel robots.

We decided to email some of the delta robot hobbyists with videos on Youtube, one of whom has already proved to be a great resource, providing us with a great deal of advice and suggestions for our delta robot. He has even graciously offered to loan us some equipment that may be out of our price range. He works as a consultant for a company called Delta Tau who manufacture motion controller systems and they are willing to sponsor a controller.

Overall, we have found the internet to be a fantastic resource for information on hardware, software, and the mechanism kinematics. This is perhaps due to the open-source 3-D printer push among hobbyists and the relative low cost of entry for beginning to tinker with a parallel robot: a versatile and amazing machine!

[1] Rocholl, Johann C. "Rostock Delta Robot." *Reprap.org*. N.p., 14 July 2012. Web. 13 Nov. 2014. <http://reprap.org/wiki/Rostock>.
[2] Bonev, Lian. "Parallelmic - The Parallel Mechanism Information Center."*Parallemic.org*. N.p., 24 Aug. 2014. Web. 13 Nov. 2014. <http://www.parallemic.org/>.

3. Journal Search

For our journal search, we used the CLIO, ProQuest, Springer, Business Source Complete, Web of Science and ASME Digital Collections. We looked at articles from the journals *Robotica*, *Applied Mechanics and Materials*, *International Journal of Advanced Robotic Systems*, *The Internal Journal of Robotics Research*, *International Journal of Engineering Trends and Technology*, and more. Through our search, we believe that one of the most useful articles we found was the following.

a. Staicu, S. (2009). “Recursive Modelling in Dynamics of Delta Parallel Robot”. *Robotica*, *27*(2), 199-207. DOI:http://dx.doi.org/10.1017/S0263574708004451

This paper performs in depth analysis on the kinematics and dynamics of delta robots. The author compares different methods for solving the inverse kinematics problem to determine the position, velocity, and acceleration of each motor based on the position, velocity, and acceleration of the end effector. An analysis of the torque output required of the motors is also performed. In doing so, the author describes the fundamental nature of the mechanics of delta robots. The analysis is very thorough, and it will help us by allowing us to calculate torques required so we may choose motors capable of providing that level of torque, and providing inverse kinematic relationships which will aid us in programming our controller. This paper also referenced 37 other papers, most of which were also about delta robot mechanics. We found a number of these papers useful as well.

4. Patent Search

For our patent search, we employed the Derwent Innovation Index and Google Patent Search. Searched terms include “delta robot”, “parallel robot”, “surgical robotics”, “calibration”, and “kinematic optimization.” We also used international patent codes 490.01 “Robotic arm”, 479.01 “Multiple controlling elements for single controlled element”, and A61F-011/00 “Methods or devices for treatment of the ears, e.g. surgical”.

a. Clavel, Reymond. Device for the Movement and Positioning of an Element in Space. Patent US4976582 A. 11 Dec. 1990. Web.

A proper patent search must include the original patent for the delta robot, invented by Reymond Clavel and published in 1990. This patent describes the idea for a robot with three kinematic chains that moves a platform through a workspace at a constant orientation. It has been referenced by almost 200 other patents, making it a great resource for finding other applicable patents. An image of the original device is included below.

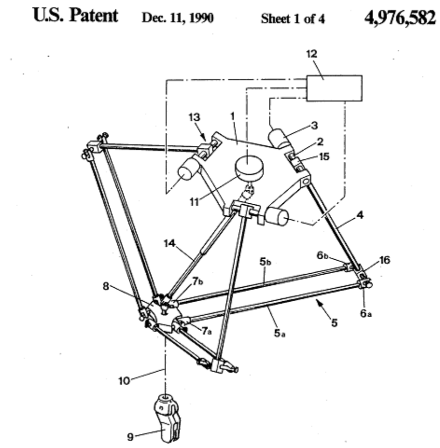

Figure 1: Original Delta Robot Design

b. Simaan, Nabil, Wei Wei, Roger Goldman, Howard Fine, and Stanley Chang. Systems, Devices, and Methods for Surgery on a Hollow Anatomically Suspended Organ. Patent CA 2663797 A1. 27 May 2008. Web.

Due to delta robots' potentially high precision and accuracy, they and other parallel robots have been popular in surgical applications. The most notable example is the SurgiScope system by DeeMed, where a camera mounted to the platform of a delta robot is used for neurosurgery. Another such system is described in a 2008 patent from Columbia University, "Systems, devices, and methods for surgery on a hollow anatomically suspended organ". This robot employs a platform driven by three robotic arms, at the end of which is mounted a serial robot with a needle used for precision injections. Our delta robot could use a similar device attached to its moving platform; possibilities include mounting a needle, a camera, or another surgical device. Adding one or two additional motors at this level would increase the robot's degrees of freedom and utility.

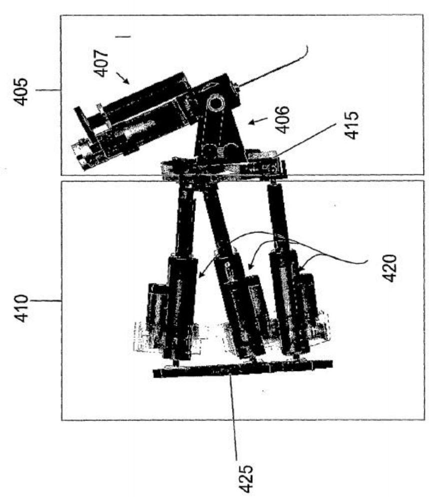

Figure 2: Surgery Delta Robot

c. ELIASSON, Gustav. Calibration Tool for a Delta Robot. Abb Technology Ltd. Patent WO 2014029448 A1. 27 Feb. 2014. Web.

As delta robots continue their rise in popularity in the medical field, the motions must be more precise than originally intended by early researchers. Early delta robots were accurate to well within a few millimeters, but if any delta robots want to make it in the cutting edge of medical research, they must be able to compete with the precision of other robots in the field that can be accurate to the millimeter to micrometer scale. This patent is for a tool that is able to calibrate the end effector of a delta robot.

When calibrating a drive arm of a Delta robot, the respective drive arm needs to be moved to a known position that is used as a reference position for the calibration. A conventional way of fixing a drive arm into a reference position is to push the drive arm all the way up until it comes into contact with a calibration pin positioned at a robot base. While this reference position is accurate enough for many applications, for other applications it is not. The position of the calibration pin in relation to the drive arm depends on a chain of tolerances between the two components, and consequently the reference position is not as accurate as desired.

The proposed method of calibration is to first set up the robot with two of the drive arms parallel to each other. The position of these two arms is recorded, and this is the reference point for calibration. Since these arms are exactly the same size, the line connecting the two ends will be exactly parallel to the ground. This is much more accurate than calibrating the linkages to an axis in the center of the robot, because it does not depend on the tolerances between a chain of components connecting one arm to another, but rather the two arms directly to each other.

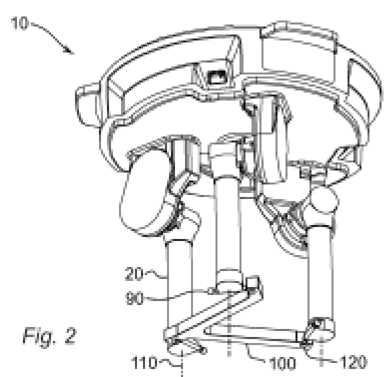

Figure 3: Calibration Tool for a Delta Robot

JOURNALS	ARTICLE	AUTHOR	URL/DOI	RELEVANCE
ROBOTICA	Recursive modelling in dynamics of Delta parallel robot	Stephan Staicu	Link	Kinematics
Ji xie gong cheng xue bao	Dynamic dimensional synthesis of delta robot	Limin Zhang	Link	Dynamic Synthesis
Intelligent Robotics and Applications: 4th Intl Conference	Stiffness Analysis of Clavel's DELTA Robot	Martin Wahle	Link	Structural
Applied Mechanics and Materials	Walking of a Delta Robot in Image Space	Boonhaijaroen, N., & Chancharoen	Link	Controls and Feedback
International Journal of Engineering Trends and Technology (IJETT)	Optimization and Design of a Laser-Cutting Machine using Delta Robot	B.Moharana , Rakesh Gupta, Bashishth Kumar Kushwaha	Link	Specific Application: Laser Cutting Tool
Future Communication, Computing, Control and Management. Vol. 1	Dynamic Modeling, Simulation and Experiment of the Delta Robot	Feng, Wang Pan	10.1007/978-3-642-27311-7_20	Dynamic Modeling, Simulation and Experiment
International journal of advanced robotic systems	Workspace and Payload-Capacity of a New Reconfigurable Delta Parallel Robot	Maya, Mauro	10.5772/54670	Alternative Kinematic Methods
ASME 2014 Conference on Information Storage and Processing Systems	Asymmetric Arm Design on Delta Robot System	Tsung-Liang Wu, Jih-Hsiang Yeh and Cheng-Chen Yang	Link	Rod Design
The International Journal of Robotics Research	Determination of Singularities in Delta-Like Manipulators*	Raffaele Di Gregorio	10.1177/0278364904039689	Kinematics and Singularities
The International Journal of Robotics Research	Fully Isotropic Four-Degrees-of-Freedom Parallel Mechanisms for Schoenflies Motion*	Marco Carricato	10.1177/0278364905053688	4 DOF vs. 3 DOF
Proceedings of the 18th Intl Symposium on Industrial Robots	DELTA a fast robot with parallel geometry**	Christoph W. Burckhardt	0948507977 (ISBN)	History, Reference to other journals
Computer Aided Surgery	Surgiscope: initial experience and perspectives for the future	Haase, Jens Jørgensen,	Link	Robotic Surgery
Minimally Invasive Neurosurgery	Image-guided neurosurgery / neuronavigation / the SurgiScope reflexions on a theme	J. Haase	Link	Robotic Surgery
Delta Robot: The Story of Success		Illian Bonev	Link	Delta robot history

PATENT #	TITLE	INVENTOR	WEBSITE	RELEVANCE
US 4976582 A	Device for the movement and positioning of an element in space	Reymond Clavel	Link	Original Design
EP 2301726 B1	Telescopic shaft for an industrial robot according to the delta concept	Daniele Bellante	Link	Additional rotational DOF on end-effector
DE 102011075418 A1	A device for moving and positioning an object in space	Mohamed Bouri, Reymond Clavel, Marc-Olivier Demaurex, Michel Huser, David Keiffer, Alain Teklits, Matthias Tschudi,	Link	Overall Design, spring damping systems
DE 102010047315 B4	Robot with parallel link arms	Katsumi Fujimoto, Satoshi Kinoshita,Hidenori Kurebayashi, Tomoaki NAGAYAMA,Tokitaka Uemura, Masahiro Yamamoto	Link	Additional rotational DOF on end-effector
DE102014101912-A1	Robot i.e. delta robot, for handling of loads in industrial environment, has actuator whose movement axis is outside and is not parallel to plane with respect to parallel movement axes of other actuators	Oldin Beheer	Link	Improving effectiveness and compactness of structure
KR1413152-B1	Ball joint for delta robot, has gas layer fixed in interval of pocket part and joint part, where layer is formed with jet hole to spray gas on outer side of pocket part, and ring-type rail part fixed in inner periphery of pocket part	Lee M	Link	Rod End/ Ball Joint Design
CN 203619682 U	Hybrid five degrees of freedom robotic minimally invasive surgery	Song C, Xu Z, Chen T	Link	Robotic surgery