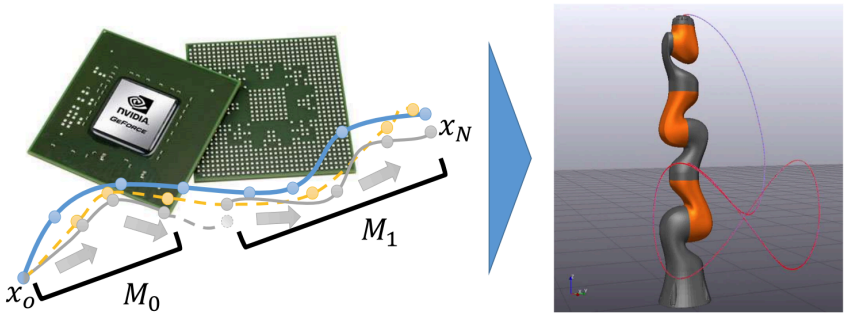
COSC 1/69.23: Parallel Optimization for Robotics



Semester: Fall 2025 | **Instructor:** Brian Plancher | **Meeting time: 2A** | **Room: TBD**

Prerequisites: Multivariable Calculus (Math 8), and C(++) Programming (COSC 50).
It would also be helpful to have prior experience with Linear Algebra/Optimization (Math 22 / COSC 70).
Contact the instructor if you have equivalent prior experience but do not have prerequisites
(e.g., prior experience with pointers, arrays, and memory management).

Enrollment Capped at 45 Students

Description:

Many stages of state-of-the-art robotics pipelines rely on the solutions of underlying optimization algorithms. Unfortunately, many of these approaches rely on simplifications and conservative approximations in order to reduce their computational complexity and support online operation. At the same time, parallelism has been used to significantly increase the throughput of computationally expensive algorithms across the field of computer science. And, with the widespread adoption of parallel computing platforms such as GPUs, it is natural to consider whether these architectures can benefit robotics researchers interested in solving computationally constrained problems online. This course will provide students with an introduction to both parallel programming on GPUs as well as numerical optimization. It will then dive into the intersection of those fields through case studies of recent state-of-the-art research and culminate in a team-based final project.

Learning Outcomes:

By the end of the semester, you will be able to:

- Analyze the opportunities and limitations of parallel programming on GPUs
- Evaluate the strengths and weaknesses of numerical optimization algorithms
- Engage critically with recent research on parallel optimization algorithms for robotics
- Collaborate with a team to develop and present an open-ended final project

Grading:

- 25% Problem Sets
- 35% Exam
- 35% Final Project Presentation, Report, and other Milestones
- 5% Attendance, Collaboration, and Participation

Requests for regrades can only be made for 1 week following the return of a grade.
All assignments are due by 11:59pm ET on the due date.

Student drop-ins (Office Hours)

See brianplancher.com/office_hours for the most up-to-date schedule!

- These are scheduled time-slots for us to chat and I will also be available by appointment in case the scheduled slot doesn't work for you!
- I strongly encourage you to come to at least one student drop-in slot per semester.
- This is your time, so you can use it however you want! Stop by for a quick chat, ask questions about the course (or give feedback), ask questions about research, ask questions about getting jobs in finance/consulting/tech, tell me about a new hit TV show, any reason is a good reason!

Course Outline:

A high-level course outline follows. View the Course Schedule below for more information.

Module 0: Introduction and Course Overview

This module lays the foundation for the course. Namely, it provides an introduction to both optimization algorithms commonly used for robotics applications as well as the opportunities for parallel programming.

Module 1: (GPU) Parallel Programming

This module provides an introduction to parallel programming with a focus on GPUs. We will cover both common software constructs as well as practical implications of hardware architectures on programming models and optimizations.

Module 2: Optimization Algorithms for Robotics

This module provides an introduction to numerical optimization with a focus on algorithms used for robotics applications. We will cover both theoretical mathematical foundations and practical application tradeoffs, constraints, and limitations.

Module 3: Putting it All Together

This module integrates Modules 1 and 2 exploring how recent robotics research has leveraged parallelism to accelerate optimization algorithms for robotics.

Module 4: Final Integrative Projects

Throughout the course we will develop an integrative, team-based, final project which will be presented during the last class.

Readings and Materials:

The course will involve the reading of technical papers, chapters of textbooks, and technical blog posts and the watching of technical videos. Specific readings and videos are listed in the detailed reading list and course scheduled below. Readings and videos can be accessed for free either as they are either open-source or will be posted to the course website. Students will not need to purchase any textbooks or other materials for this course. In particular, all GPU programming will leverage cloud-based platforms to ensure that no students need to purchase additional computer hardware.

Email and Slack Policy:

I request that as much as possible you use Slack (instead of email) for all course-related questions. Please post liberally as if you have a question, another student likely has a similar question. There is also an anonymous bot if you would like to submit anonymously. I will try to respond to all Slack posts as soon as possible during working hours and at least within 1 business day. **Click this link to sign up for our course Slack**. If you do need to reach me via email, please send the email to the following address: plancher+courses@dartmouth.edu. I will *try* to respond to emails within 2 business days.

Gradescope and Regrade Policy:

We will be using Gradescope for problem set submission and autograding. All coding assignments with autograders can be submitted an infinite amount of times until the deadline. As such, re-grades on such assignments will only be allowed in extenuating circumstances. Other assignments will be manually graded following submission. All re-grade requests for such assignments must be submitted as a private message on Slack and will only be accepted for one week following the return of a grade. Do note that grades could go up or down following a re-grade.

Late and Missed Assignments Policy:

An assignment is considered **LATE** if not turned in by the date and time as specified on the assignment. Late assignments will receive a **33%** penalty per day (24-hour period) late. Note that weekdays, weekend days, holidays, etc. all equally count as one day. Also if an assignment is in multiple parts (e.g., coding and written), it counts as one day late if you turn in either or both parts one day late. For **PROBLEM SETS ONLY**, you are permitted **2** "late days," to be used as you wish throughout the semester. To use a "late day," simply submit your work with a note to the course staff that indicates how many "late days" your submission has incurred and how many remaining "late days" remain, if any. When possible, advance notice is appreciated.

If there is a situation that you feel should be exempt from this policy and deserves an additional extension, you must reach out over email at least 2 weeks prior to the due date. Note that this also applies to rescheduling exams, presentations, etc. For missed deadlines without prior notification, extension, and approval due to illness or other emergencies, please reach out ASAP and include a doctor's note or other official documentation to verify and validate the emergency. Finally, events that are known in advance do not constitute legitimate reasons for extensions (e.g., conferences, sporting events, other exams, family celebrations); please make sure to plan ahead accordingly.

Use of AI Content Generators:

I view AI tools as a powerful resource that you will likely leverage in the future. As such, the use of AI-based content generation tools, such as ChatGPT, is permitted in this course. However, you will be required to disclose any use of AI tools for each assignment.

The goal of this policy is to help you develop your resilience to automation, as these tools will become increasingly prevalent in the future, and also to learn about their weaknesses. By incorporating these tools into your work process, you will be able to focus on skills that will remain relevant despite the rise of automation. However, **it is important to note that AI tools are susceptible to errors** (e.g., most citations are incorrect). As a student, it is your responsibility to ensure the quality and appropriateness of the work you submit in this course. As such please make sure to read carefully (and likely heavily edit) the output from such tools. Also, please be mindful of the data you provide to these systems, as your work may contain private information, not just your own but also that of others. For example, you should never enter the names of study participants into ChatGPT. Furthermore, there is a risk of inadvertently

plagiarizing when using these tools as they often draw content without proper citation. Standard plagiarism policies will apply to all assignment submissions, and “AI did it!” is not a sufficient excuse. To prevent this, you can consider using more responsible tools that are designed to cite their data sources, and in either case you should make sure to add citations where appropriate yourself. Lastly, be aware of the dangers of becoming overly dependent on these tools. While they can be incredibly useful, relying on them too much can diminish your own critical thinking and writing skills.

If you do not wish to use these tools, that is a valid decision. The use of AI tools in education can be messy and unpredictable due to the risks mentioned earlier. You may have moral confusion or concerns about the uncertainty associated with using AI tools in their coursework. This policy aims to anticipate and mitigate any potential harms associated with AI tool usage, rather than promoting their use.

For every assignment submission, you are required to include an “AI Tool Disclosure” paragraph which states to what extent you used AI tools. We will not mark you down for the use or non-use of AI tools. The course staff simply wants to understand the prevalence of AI tool use and methods of use to better adapt course policies and teaching practices for the future.

Academic Integrity:

Dartmouth's Academic Honor Principle states: "Academic integrity is foundational to a Dartmouth education. All members of the Dartmouth community—faculty, staff, and students—are responsible for maintaining a culture of integrity, honesty, and respect in teaching, learning, scholarship, and creative work. By upholding this principle, we foster an atmosphere of intellectual growth and personal development both within and beyond Dartmouth."

As this course likely draws in a diverse cohort of students I would also like to draw your attention to the various specific honor codes for your school:

- MD students follow the Geisel School of Medicine's Student Honor Code.
- MBA students follow the Tuck School of Business' *Academic Honor Principle* found in their Student Handbook (Sharepoint).
- PhD, MS, MA, MALS, MFA, and graduate special students in the Guarini School of Graduate and Advanced Studies and MHCDS, MHS, and MPH students follow the Academic Honor Policy for Graduate and Professional Students.
- BE, MEng, MS, MEM, and PhD students in the Thayer School of Engineering follow Thayer's Academic Honor Policy.
- AB undergraduates and special non-degree seeking students follow the Academic Honor Policy for Undergraduate Students in the Arts and Sciences.

This course’s specific policy on academic integrity builds on these honor codes and is best stated as "be reasonable." We recognize that interactions with classmates and others can facilitate mastery of the course’s material. As this course revolves mostly around team projects we expect students to collaborate heavily and work together on those assignments. Even on individual assignments students should feel encouraged to ask classmates and others for conceptual help. However, there remains a line between asking for help and submitting someone else’s work. Especially on individual assignments, make sure this collaboration does not reduce to your classmate doing your work for you (e.g., writing your response, copy-pasting code, or making your slides). If in doubt as to whether some act is reasonable, ask first! The course staff would much rather have a conversation about extensions than about academic integrity! We hope you are reading these policies (or at least skimming them), so if you are, please send the course instructor an email with a (robotics) pun/joke/meme with the subject “academic integrity easter egg” and if you come by office hours I’ll give you a prize (exact prize subject to availability)! Acts considered not reasonable will be reported, and the course reserves the right to impose local sanctions on top of that

outcome. **If you commit some act that is not reasonable but bring it to the attention of the course staff within 48 hours, the course may impose local sanctions, but the course will not refer the matter further except in cases of repeated acts.**

Diversity, Inclusion, Accessibility, and Accommodations:

In an ideal world, science would be objective. However, much of science is subjective and is historically built on a small subset of privileged voices. We acknowledge that it is possible that there may be both overt and covert biases in the material due to the lens with which it was written, even though the material is primarily of a scientific nature. Since integrating a diverse set of experiences is important for a more comprehensive understanding of science please contact the course staff (in person or electronically) or submit anonymous feedback if you have any suggestions to improve the quality of the course materials. We would also like to create a learning environment that supports diversity of thoughts, perspectives, and experiences, and honors your identities. If you have a name and/or set of pronouns that differ from those that appear in your official records, please let us know!

We also note that our community is composed of students from a variety of financial backgrounds. Socioeconomic diversity can be invisible, and you may be experiencing financial difficulties related to the cost of textbooks, materials, or other necessities for our class of which we are not aware. If you encounter financial challenges related to this class, there may be sources of support for you. If you feel comfortable sharing your experience with us, you may. You may also consider meeting with a financial aid officer to discuss options, reaching out to the First-Generation Office if you are a first-generation student, browsing the Funding Resources page, or, applying for the Dartmouth 4E Fund which provides supplemental funds for essentials, enrichment, experiences, and emergencies.

We also note that the academic environment is challenging, our terms are intensive, and classes are not the only demanding part of your life. There are a number of resources available to you on campus to support your wellness, including: the Counseling Center which allows you to book triage appointments online, the Student Wellness Center which offers wellness check-ins, and your undergraduate dean. The student-led Dartmouth Student Mental Health Union and their peer support program may be helpful if you would like to speak to a trained fellow student support listener. If you need immediate assistance, please contact the counselor on-call at (603) 646-9442 at any time.

Dartmouth also has a deep commitment to support students' religious observances and diverse faith practices. Some students may wish to take part in religious observances that occur during this academic term. If you have a religious observance that conflicts with your participation in the course, please meet with me as soon as possible—before the end of the second week of the term at the latest—to discuss appropriate course adjustments.

Student Accessibility and Accommodations

Students requesting disability-related accommodations and services for this course are required to register with Student Accessibility Services (SAS; Apply for Services webpage; student.accessibility.services@dartmouth.edu; (603) 646-9900) and to request that an accommodation email be sent to me in advance of the need for an accommodation. Then, students should schedule a follow-up meeting with me to determine relevant details such as what role SAS or its Testing Center may play in accommodation implementation. This process works best for everyone when completed as early in the quarter as possible. If students have questions about whether they are eligible for accommodations or have concerns about the implementation of their accommodations, they should contact the SAS office. All inquiries and discussions will remain confidential.

Title IX:

At Dartmouth, we value integrity, responsibility, and respect for the rights and interests of others, all central to our Principles of Community. We are dedicated to establishing and maintaining a safe and inclusive campus where all community members have equal access to Dartmouth's educational and employment opportunities. We strive to promote an environment of sexual respect, safety, and well-being. Through the Sexual and Gender-Based Misconduct Policy (SMP), Dartmouth demonstrates that sex and gender-based discrimination, sex and gender-based harassment, sexual assault, dating violence, domestic violence, stalking, etc., are not tolerated in our community. For more information regarding Title IX and to access helpful resources, visit Title IX's website (sexual-respect.dartmouth.edu). As a faculty member, I am required to share disclosures of sexual or gender-based misconduct with the Title IX office. If you have any questions or want to explore support and assistance, please contact the Title IX office at 603-646-0922 or TitleIX@dartmouth.edu. Speaking to Title IX does not automatically initiate a college resolution. Instead, much of their work is around providing supportive measures to ensure you can continue to engage in Dartmouth's programs and activities.

Consent to Recording:

I'll be recording all of our class meetings, so that those who cannot be there due to unforeseen circumstances can watch later. Dartmouth has asked that I include the following language describing some bounds on how recording should be used. You do not need to send me any sort of agreement on this – it just makes clear that you shouldn't record or distribute any recordings without my consent.

Consent to recording of course and group office hours

- I affirm my understanding that this course and any associated group meetings involving students and the instructor, including but not limited to scheduled and ad hoc office hours and other consultations, may be recorded within any digital platform used to offer remote instruction for this course;
- I further affirm that **the instructor owns the copyright** to their instructional materials, of which these recordings constitute a part, and distribution of any of these recordings in whole or in part without prior written consent of the instructor may be subject to discipline by Dartmouth up to and including expulsion;
- I authorize Dartmouth and anyone acting on behalf of Dartmouth to record my participation and appearance in any medium, and to use my name, likeness, and voice in connection with such recording; and
- I authorize Dartmouth and anyone acting on behalf of Dartmouth to use, reproduce, or distribute such recording without restrictions or limitation for any educational purpose deemed appropriate by Dartmouth and anyone acting on behalf of Dartmouth.

Requirement of consent to one-on-one recordings.

- By enrolling, I hereby affirm that I will not under any circumstance make a recording in any medium of any one-on-one meeting with the instructor without obtaining the prior written consent of all those participating, and I understand that if I violate this prohibition, I will be subject to discipline by Dartmouth up to and including expulsion, as well as any other civil or criminal penalties under applicable law.

Assignment Descriptions:

Problem Sets (25%)

Purpose:

- Develop foundational skills and confidence in parallel programming and numerical optimization to prepare for the final project and future courses, research, and industry jobs.

Students will work through a series of coding and theoretical problems in order to develop parallel programming and optimization skills. This will both help prepare students for final projects and help develop skills they can use in future courses and jobs. Each problem set will be paired with an in-class "party" to aid in collaborative problem solving although students must submit their own answers.

Exam (35%)

Purpose:

- To reinforce and validate knowledge learned across both optimization and parallel programming including both theoretical foundations and practical applications for use on the final project, and future courses, research, and industry jobs.

The exam will be held in-class, closed-book, no notes except the possibility of a "cheat sheet." It will cover all of the course material presented in both the optimization and parallel programming modules of the course. See the schedule for dates and topics covered. A review will be held preceding the exam. The exam will be designed to test knowledge useful for future work and validate your knowledge of both the core mathematical and computational foundations explored in this course and their applications.

Final Project Presentation, Report, and other Milestones (35%)

Writeup Purpose:

- Develop the skill of developing a team-based project report
- Get feedback on technical writing skills (and practice using LaTeX)

Presentation Purpose:

- Develop the skill of presenting a team-based project to an audience
- Get feedback on presentation skills both in terms of delivery and slides

Other Milestones Purpose:

- Develop a project proposal and get feedback early and often on a project design and plan

Students will work in small teams of 2-4 students (special requests must be made for smaller or larger groups) on a final integrative project and each team will be asked to provide a technical report on and present their final project. The report will be in the form of a standard academic publication. A few resources on writing academic papers can be found here, here, and here. We will use LaTeX for writing the report as it is standard practice in computer science. Overleaf is an online editor (think Google Docs) that allows you to write LaTeX and never have to work on package management, installation, setup etc. They also have a great guide for getting started (and the course staff will upload a skeleton project you can copy with all of the necessary templates). The presentation should be supported by slides. Two guides for good slide design can be found here and also here. Also, here is a guide on effective presentations. More details on the final project will be distributed later in the semester. Note that the final presentation may occur during the exam period.

Attendance, Collaboration, and Participation (5%)

Purpose:

- To develop collaboration and teamwork skills

This course is capped to a moderate size to enable interaction. As such you are expected to attend lectures and participate in class discussions. Similarly as the final project will be done in collaboration with other students, collaboration and group participation will be key skills you will need to work on during this class. This is intentional as most of your future work environments will rely heavily on teamwork and team based projects and presentations whether you go into technology or business in industry or academia.

Preliminary Detailed Reading List:

There are no required textbooks for this class. However, as many students prefer to have a companion text we have provided relevant technical papers, chapters of textbooks, and technical blog posts and videos to accompany each lecture as listed in the detailed course scheduled below. Readings and videos can be accessed for free either as they are open-source or through the school library or will be posted to the course website. Students will not need to purchase any textbooks or materials for this course.

Textbooks

- Stuart J. Russell. *Artificial Intelligence a Modern Approach*. Pearson Education, Inc., 2010.
- Stephen P. Boyd and Lieven Vandenberghe. *Convex Optimization*. Cambridge University Press, 2004.
- Jorge Nocedal and Stephen J. Wright. *Numerical Optimization*. Springer, 1999.
- Tedrake, Russ. *Underactuated Robotics*. Online, 2022.
- Michael S Kirkpatrick. "OpenCSF: An Online Interactive Textbook for Computer Systems Fundamentals." *Proceedings of the 49th ACM Technical Symposium on Computer Science Education*. 2018.
- Matthews, Suzanne J., Tia Newhall, and Kevin C. Webb. *Dive Into Systems: A Gentle Introduction to Computer Systems*. No Starch Press, 2022.
- David B. Kirk and W. Hwu Wen-Mei. *Programming Massively Parallel Processors: a Hands-On Approach*. Morgan Kaufmann, 2016.

Peer-Reviewed Papers

- Hadi Esmaeilzadeh, Emily Blem, Renée St. Amant, Karthikeyan Sankaralingam, and Doug Burger. "Dark Silicon and the End of Multicore Scaling." *International Symposium on Computer Architecture*. 2011.
- Brian Plancher and Scott Kuindersma. "A Performance Analysis of Parallel Differential Dynamic Programming on a GPU." *International Workshop on the Algorithmic Foundations of Robotics*. Springer, Cham, 2018.
- Grady Williams, Andrew Aldrich, and Evangelos A. Theodorou. "Model Predictive Path Integral Control: From Theory to Parallel Computation." *Journal of Guidance, Control, and Dynamics* 40.2. 2017.
- Brian Plancher, Sabrina M. Neuman, Radhika Ghosal, Scott Kuindersma, and Vijay Janapa Reddi. "GRiD: GPU-Accelerated Rigid Body Dynamics with Analytical Gradients." *International Conference on Robotics and Automation*. 2022.

Other Resources

- Garrett Thomas. "Mathematics for Machine Learning." University of California, Berkeley (2018).
- Nick White. “Git Tutorial For Dummies.” 2021. https://www.youtube.com/watch?v=mJ-qvsxPHpY
- Mike Bailey. “Parallel Programming: Speedups and Amdahl’s law.” 2021. https://web.engr.oregonstate.edu/~mjb/cs575/Handouts/speedups.and.amdahls.law.1pp.pdf

Preliminary Course Schedule:

Week	Day	Date	Topic	Description	Assignments	Readings	Module
0	T	Sep 16	Intro Class	Overview of the Course, Nuts and Bolts, Optimization in Robotics, Thinking in Parallel	PS 0 Released (W): Math and Coding Background and Environment	Intro to Git [1,2] Math Reference Dive Into Systems Ch 1.2	(GPU) Parallel Programming
0	Th	Sep 18	GPU Parallel Computing	Basic GPU Parallelism and CUDA 101 (Blocks, Threads, etc.)		Dark Silicon Dive Into Systems Ch 11 OpenCSF Ch 6.1-6.3, 7.1-7.2	
1	T	Sep 23	(GPU) Systems Programming	Review of CUDA Basics and the Memory Hierarchy			
1	Th	Sep 25	Cuda Programming 102	Kernel Launching, Shared, Global, Local, Host, and Unified Memory, I/O, Reductions, Atomics, Race Conditions	PS 0 Due (Th) PS 1 Released (Th): Systems and GPU Parallel Programming	Dive Into Systems Ch 14,15 Kirk Ch 2, 3.1-3.2, 4.1-4.5, 5.1, 6.1	
2	T	Sep 30	Advanced CUDA Topics				
2	WX	Oct 1	PS1 "Party"				
2	Th	Oct 2	Convex Optimization and Vector Calculus	Convexity, Global vs. Local Optima, Gradient Descent, Vector Calculus	PS 1 Due (Th) PS 2 Released (Th): Optimization	Boyd Ch 1.1-1.4, 2.1, 3.1-3.1.4	Optimization Algorithms for Robotics
3	T	Oct 7	Nonlinear Optimization for Robotics	Taylor Expansions, Line Searches, Solving Linear Systems		Nocedal Ch 2 Underactuated Ch 1.1-1.6, 2	
3	Th	Oct 9	Constrained Optimization for Robotics	Penalty Methods, (Augmented) Lagrangian, KKT System			
4	T	Oct 14	Advanced Optimization Topics Part 1	Direct Colocation, More Solving Linear Systems, iLQR/DDP and Bellman/Dynamic Programming		AIMA Ch 17.1-17.3 Underactuated Ch 7.1-7.3, 8.1-8.2, 10-10.4	
4	WX	Oct 15	PS2 "Party"				

4	Th	Oct 16	Advanced Optimization Topics Part 2	Differentiable Optimization and Machine Learning	PS 2 Due (Th)		
5	T	Oct 21	Module 1+2 Review **Pre-Recorded**				Putting it All Together
5	Th	Oct 23	Exam		Project Instructions Released (F)		
6	T	Oct 28	Putting it All Together: Parallelism in Robotics Optimization	Project Overview, Parallel DDP, GRiD and Code-Generation, Instruction vs. Algorithm Level Parallelism		MPPI Paper GRiD Paper PDDP Paper	
6	Th	Oct 30					
7	T	Nov 4	Project Proposal Meetings		Project Proposal Due (M)		Final Project
7	Th	Nov 6	Final Project Lab Time				
8	T	Nov 11					
8	Th	Nov 13	Project Update Meetings		Project Update Due (W)		
9	T	Nov 18	Final Project Lab Time				
Ex	TBD	TBD	Final Project Presentations		Project Report Due		