Colorado State University
GLOBAL CAMPUS

CSC430: PRINCIPLES OF ROBOTICS THEORY

Credit Hours: 3

Contact Hours: This is a 3-credit course, offered in accelerated format. This means that 16 weeks of material is covered in 8 weeks. The exact number of hours per week that you can expect to spend on each course will vary based upon the weekly coursework, as well as your study style and preferences. You should plan to spend 14-20 hours per week in each course reading material, interacting on the discussion boards, writing papers, completing projects, and doing research.

Faculty Information: Faculty contact information and office hours can be found on the faculty profile page.

COURSE DESCRIPTION AND OUTCOMES

Course Description:

This course provides an introduction to the application of robotic systems in computing. Primary emphasis will be on understanding robotic mechanics, intelligent controls and associated dynamics. Students will develop an understanding of robot manipulation and noise reduction techniques. Focus will be on applying computer vision principles for the systematic control of robot components.

Course Overview:

In this course, you will be introduced to the mathematical and algorithmic foundations for modern robotics. Topics include rigid body motion, forward and inverse kinematics, trajectory generation, robot dynamics and control. The assignments will involve mathematical derivations/proofs and simulation programming dynamical systems inherent with robot dynamics. You are expected to have a solid math background. Prior experience in Python will be helpful.

- This class is not about actually building a robot. To gain hands on experience, you should take other classes like mechatronics, embedded systems, mechanical design, etc.
- This class incorporates a considerable amount of mathematics, particularly linear algebra and differential equations.

Course Learning Outcomes:

1. Identify principles associated with robotic construction.
2. Discuss the spatial considerations of a robotic system.
3. Demonstrate how to model the basic components of a robot.
4. Apply techniques to control the motion of a robotic system.
5. Implement techniques for manipulating the behavior of a robot in a given system.
6. Demonstrate how to reduce noise components that may affect a robot's behavior in a given system.
7. Apply computer vision principles to control robotic components.

PARTICIPATION & ATTENDANCE

Prompt and consistent attendance in your online courses is essential for your success at CSU-Global Campus. Failure to verify your attendance within the first 7 days of this course may result in your withdrawal. If for some reason you would like to drop a course, please contact your advisor.

Online classes have deadlines, assignments, and participation requirements just like on-campus classes. Budget your time carefully and keep an open line of communication with your instructor. If you are having technical problems, problems with your assignments, or other problems that are impeding your progress, let your instructor know as soon as possible.

COURSE MATERIALS

Required:

The primary textbook is:

- Lynch, K., & Park, F. (2017). *Modern robotics: Mechanics, planning, and control*. Cambridge, United Kingdom: Cambridge University Press. ISBN 9781107156302.
    - This book is freely available and may be downloaded from http://hades.mech.northwestern.edu/index.php/Modern_Robotics#Book

Additional Required Resources:

- Chasnov, J. (2018). *Matrix algebra for engineers*. Retrieved from https://bookboon.com/en/matrix-algebra-for-engineers-ebook
- Kuttler, K. (2012). *Linear algebra I: Matrices and row operations*. Retrieved from https://bookboon.com/en/linear-algebra-i-matrices-and-row-operations-ebook
- Murray, R. Li, Z., & Sastry, S. (1994). *A mathematical introduction to robotic manipulation.* Boca Raton, FL: CRC Press. Retrieved from https://www.cds.caltech.edu/~murray/books/MLS/pdf/mls94-complete.pdf
- Stengel, R. (2017). *Robotics and intelligent systems: A virtual reference book*. Princeton, NJ: Princeton University. Retrieved from http://www.stengel.mycpanel.princeton.edu/RISVirText.html
- Verwoerd, W. (2017). *Matrix methods and differential equations: A practical introduction*. Retrieved from https://bookboon.com/en/matrix-methods-and-differential-equations-ebook
- NumPy Quickstart Tutorials:
    - https://docs.scipy.org/doc/numpy/user/quickstart.html
    - http://cs231n.github.io/python-numpy-tutorial/

***NOTE:** All non-textbook required readings and materials necessary to complete assignments, discussions, and/or supplemental or required exercises are provided within the course itself. Please read through each course module carefully.*

COURSE SCHEDULE

Due Dates

The Academic Week at CSU-Global begins on Monday and ends the following Sunday.

- **Discussion Boards:** The original post must be completed by Thursday at 11:59 p.m. MT and Peer Responses posted by Sunday 11:59 p.m. MT. Late posts may not be awarded points.
- **Opening Exercises:** Take the opening exercise before reading each week's content to see which areas you will need to focus on. You may take these exercises as many times as you need. The opening exercises will not affect your final grade.
- **Mastery Exercises:** Students may access and retake mastery exercises through the last day of class until they achieve the scores they desire.
- **Critical Thinking:** Assignments are due Sunday at 11:59 p.m. MT.

WEEKLY READING AND ASSIGNMENT DETAILS

Module 1

Readings

- Chapters 2-4 & 6-8 in *Matrix Methods and Differential Equations, A Practical Introduction*

Opening Exercise (0 points)

Discussion (25 points)

Mastery Exercise (10 points)

Critical Thinking: (60 points)

Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option #1: Simulate the State Trajectory for 100 Steps

Use Python (linked in assignment) to simulate the state trajectory of the following system for 100 steps. Plot the state trajectories $x_1(k)$ and $x_2(k)$ on the same figure. Submit your code and plot. You should use matplotlib for graphing.

$$x(k+1) = \begin{bmatrix} \cos(0.05) & -\sin(0.05) \\ \sin(0.05) & \cos(0.05) \end{bmatrix} x(k), \qquad x(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

Option #2: Simulate the State Trajectory for 100 Steps

Use Python (linked in assignment) to simulate the state trajectory of the following system for 100 steps. Plot the state trajectories $x_1(k)$ and $x_2(k)$ on the same figure. Submit your code and plot. You should use matplotlib for graphing.

$$x(k+1) = \begin{bmatrix} \cos(0.05) & \sin(0.05) \\ -\sin(0.05) & \cos(0.05) \end{bmatrix} x(k), \qquad x(0) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Module 2

Readings

- Chapter 2 in *Modern Robotics: Mechanics, Planning, and Control*

Opening Exercise (0 points)

Discussion (25 points)

Mastery Exercise (10 points)

Critical Thinking: (60 points)

Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Number of Degrees of Freedom of Your Arm and From Your Torso to Palm (Lynch & Park Exercise 2.2)

Find the number of degrees of freedom of your arm, from your torso to your palm (just past the wrist, not including finger degrees of freedom). Keep the center of the ball-and-socket joint of your shoulder stationary (do not "hunch" your shoulders) Find the number of degrees of freedom in two ways:

- Add up the degrees of freedom at the shoulder, elbow, and wrist joints.
- Fix your palm at on a table with your elbow bent and, without moving the center of your shoulder joint, investigate how many degrees of freedom you can still move your arm.

In a one- to two-page paper, answer the following questions:

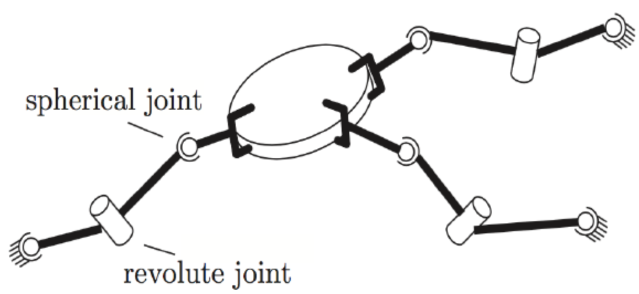
- Do your answers agree?
- How many constraints were placed on your arm when you placed your palm at a fixed configuration on the table?

Requirements

- Your paper should be one to two pages in length in addition to the required title and reference pages.
- Your paper should include one to two scholarly or peer-reviewed sources.
- Your paper should be formatted according to the CSU-Global Guide to Writing and APA.

Option 2: Number of Degrees of Freedom of a System (Lynch & Park Exercise 2.7)

Three identical SRS open-chain arms are grasping a common object, as shown in the figure. Find the number of degrees of freedom for this system.



(Source: Lynch & Park, 2017, Figure 2.17)

In a one- to two-page paper, answer the following questions:

- Suppose there are now a total of n such arms grasping the object. How many degrees of freedom does the system have?

- Suppose the spherical wrist joint in each of the *n* arms is now replaced by a universal joint. How many degrees of freedom does this system have?

Requirements

- Your paper should be one to two pages in length in addition to the required title and reference pages.
- Your paper should include one to two scholarly or peer-reviewed sources.
- Your paper should be formatted according to the CSU-Global Guide to Writing and APA.

Module 3

Readings

- Chapter 3 in *Modern Robotics: Mechanics, Planning, and Control*

Opening Exercise (0 points)

Discussion (25 points)

Mastery Exercise (10 points)

Critical Thinking: (60 points)

Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Lynch & Park Exercise 3.1

In terms of the $\widehat{x_s}$, $\widehat{y_s}$, $\widehat{z_s}$ coordinates of a fixed space frame {s}, the frame {a} has its $\widehat{x_a}$-axis pointing in the direction (0,0,1) and its $\widehat{y_a}$-axis pointing in the direction (-1,0,0), and the frame b has its $\widehat{x_b}$- axis pointing in the direction (1,0,0) and its $\widehat{y_b}$-axis pointing in the direction (0,0,-1). Submit a Word document in which you complete the following:

- Draw by hand the three frames, at different locations so that they are easy to see.
- Write down the rotation matrices R_{sa} and R_{sb}.
- Given R_{sb}, how do you calculate R_{sb}^{-1}without using the matrix inverse? Write down R_{sb}^{-1} and verify its correctness using your drawing.
- Given R_{sa} and R_{sb}, how do you calculate R_{ab} without using matrix inverses? Compute the answer and verify its correctness using your drawing.
- Let R = R_{sb} be considered as a transformation operator consisting of a rotation about $\hat{x}$ by $-90°$. Calculate $R_1 = R_{sa}R$, and think of R_{sa} as a representation of an orientation, R as a rotation of R_{sa}, and R_1 as the new orientation after the rotation has been performed. Does the new orientation R_1correspond to a rotation of R_{sa} by $-90°$ about the world-fixed $\widehat{x_s}$- axis or about the body-fixed $\widehat{x_a}$- axis? Now calculate $R_2 = RR_{sa}$. Does the new orientation R_2 correspond to a rotation of R_{sa} by $-90°$ about the world-fixed $\widehat{x_s}$- axis or about the body-fixed $\widehat{x_a}$- axis?
- Use R_{sb} to change the representation of the point p_b = (1, 2, 3) (which is in {b} coordinates) to {s} coordinates.
- Choose a point p represented by $p_s = (1,2,3)$ in {s} coordinates. Calculate $p' = R_{sb}p_s$ and $p'' = R_{sb}^{T}p_s$. For each operation, should the result be interpreted as changing coordinates (from the {s} frame to {b}) without moving the point p or as moving the location of the point without changing the reference frame of the representation?

- Calculate the matrix exponential corresponding to the exponential coordinates of rotation $\omega\Theta = (1,2,0)$. Draw the corresponding frame relative to {s}, as well as the rotation axis $\widehat{\omega}$.

Option 2: Lynch & Park Exercise 3.4

In this exercise you are asked to prove the property $R_{ab}R_{bc} = R_{ac}$.

Submit a Word document in which you complete the following:

Define the unit axes of the frames {a}, {b}, and {c} by the triplets of orthogonal unit vectors $\{\widehat{x_a}, \widehat{y_a}, \widehat{z_a}\}$, $\{\widehat{x_b}, \widehat{y_b}, \widehat{z_b}\},\ and\ \{\widehat{x_c}, \widehat{y_c}, \widehat{z_c}\}$, respectively.

Suppose that the unit axis of frame {b} can be expressed in terms of the unit axes of frame {a} by

$$\widehat{x_b} = r_{11}\widehat{x_a} + r_{21}\widehat{y_a} + r_{31}\widehat{z_a}$$
$$\widehat{y_b} = r_{12}\widehat{x_a} + r_{22}\widehat{y_a} + r_{32}\widehat{z_a}$$
$$\widehat{z_b} = r_{13}\widehat{x_a} + r_{23}\widehat{y_a} + r_{33}\widehat{z_a}$$

Similarly, suppose that the unit axis of frame {c} can be expressed in terms of the unit axes of frame {b} by

$$\widehat{x_c} = s_{11}\widehat{x_b} + s_{21}\widehat{y_b} + s_{31}\widehat{z_b}$$
$$\widehat{y_c} = s_{12}\widehat{x_b} + s_{22}\widehat{y_b} + s_{32}\widehat{z_b}$$
$$\widehat{z_c} = s_{13}\widehat{x_b} + s_{23}\widehat{y_b} + s_{33}\widehat{z_b}$$

From the above, prove $R_{ab}R_{bc} = R_{ac}$.

Module 4

Readings

- Chapters 4 & 5 in *Modern Robotics: Mechanics, Planning, and Control*

Opening Exercise (0 points)

Discussion (25 points)

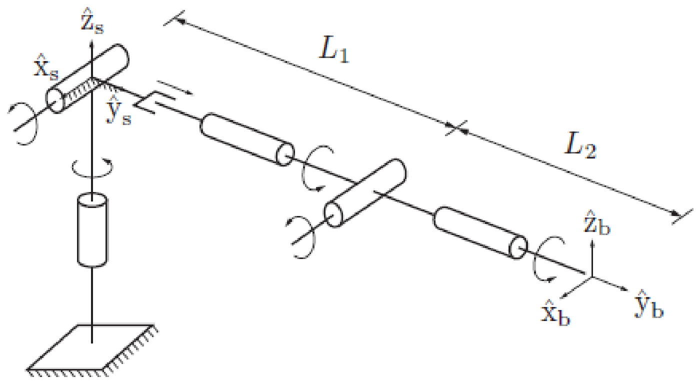
Mastery Exercise (10 points)

Critical Thinking: (60 points)

Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Lynch & Park Exercise 4.4

Determine the end-effector frame screw axes B_i for the RRPRRR robot shown in the figure below:



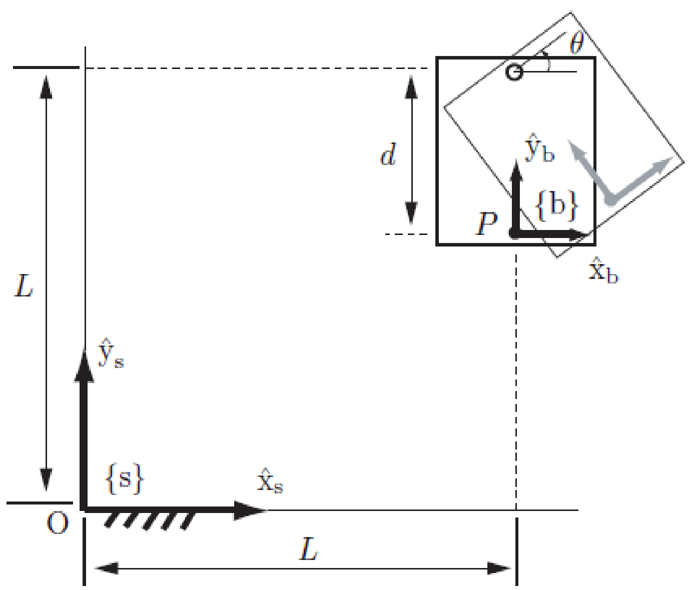
(Source: Lynch & Park, 2017, Figure 4.5)

Show all work and submit your answer as a Word document.

Option 2: Lynch & Park Exercise 5.5

Referring to the figure below, a rigid body, shown at the top right, rotates about the point (L,L) with angular velocity $\theta = 1$.

- Find the position of point P on the moving body relative to the fixed reference frame {s} in terms of θ.
- Find the velocity of point P in terms of the fixed frame.
- What is T_{sb}, the configuration of frame {b}, as seen from the fixed frame {s}?
- Find the twist of T_{sb} in body coordinates and in space coordinates. What is the relationships between those twists?
- Submit your solution in a Word document.



(Source: Lynch & Park, 2017, Figure 5.17)

Module 5

Readings

- Chapter 6 in *Modern Robotics: Mechanics, Planning, and Control*

Opening Exercise (0 points)

Discussion (25 points)

Mastery Exercise (10 points)

Critical Thinking: (80 points)

Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Lynch & Park Exercise 6.15

For matrices A, B, C, and D, if A^{-1} exists, show that

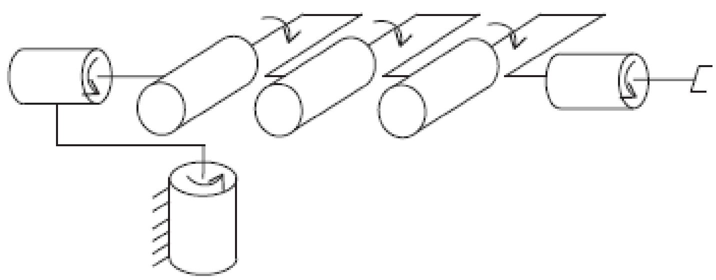
$$\begin{bmatrix} A & D \\ C & B \end{bmatrix}^{-1} = \begin{bmatrix} A^{-1} + EG^{-1}F & -EG^{-1} \\ G^{-1}F & G^{-1} \end{bmatrix}$$

where $G = B - CA^{-1}D, E = A^{-1}D, and\ F = CA^{-1}$.

Submit your solutions as a Word document.

Option 2: Lynch & Park Exercise 6.2

Solve the inverse position kinematics of the 6R open chain as shown. Submit your solution as a Word document.



(Source: Lynch & Park, 2017, Figure 6.9)

Portfolio Project Milestone: (0 points)

V-Rep Robotic Simulator

For your final Portfolio, you will simulate robotic motion using the V-Rep Robotic Simulator. You will use the Python code that comes with your textbook. The Python code is freely available from the MR code library linked in the assignment.

Click in the assignment for instructions on how to install the V-REP simulator.

Work through steps 1–6.

Module 6

Readings

- Chapter 9 in *Modern Robotics: Mechanics, Planning, and Control*

Opening Exercise (0 points)

Discussion (25 points)

Mastery Exercise (10 points)

Critical Thinking: (50 points)

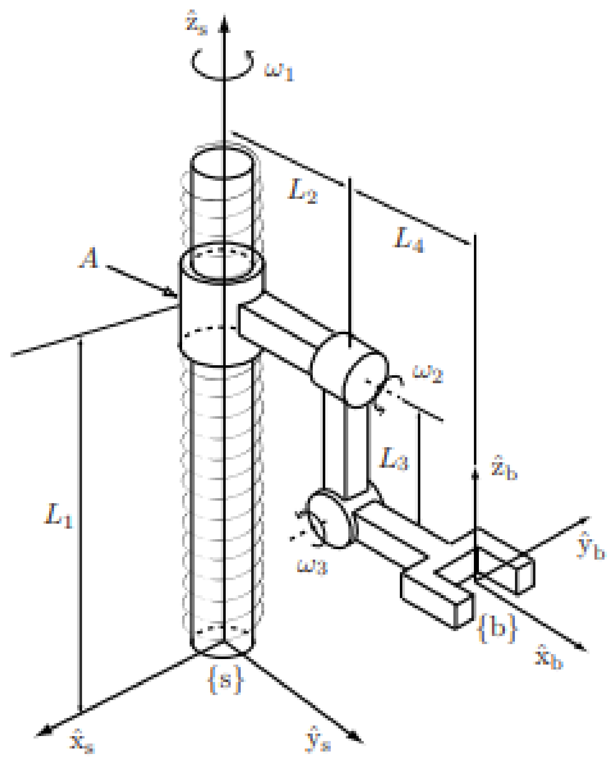
Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Zero position Configuration

The HRR robot is shown in its zero position below. The first joint is a screw joint with pitch h = 2. The link lengths are $L_1 = 10, L_2 = L_3 = 5, L_4 = 3$

Determine the zero-position configuration M of the end-effect frame {b}.

Submit your solution as a Word document. Justify your solution.

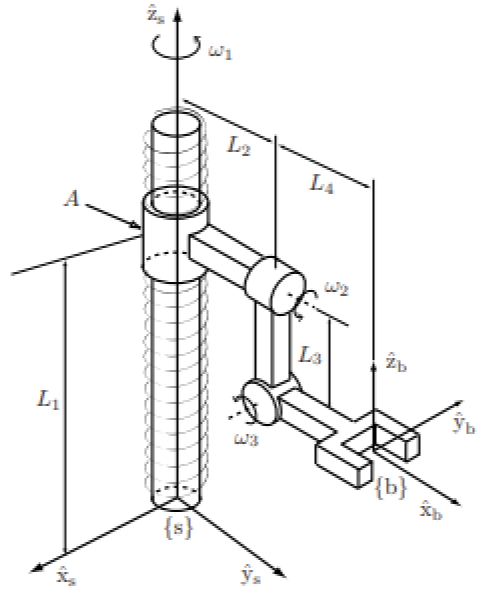


(Source: Lynch & Park, 2017, Figure 6.12)

Option 2: Forward Kinematics

Find the forward kinematics $T_{sb}(\theta_1, \theta_2, \theta_3)$. Hint: Find $S_1, S_2, and\ S_3$.

Submit and justify your solution in a Word document.



(Source: Lynch & Park, 2017, Figure 6.12)

Module 7

Readings

- Chapters 11 – 16 in *Robotics, Vision and Control: Fundamental Algorithms In MATLAB*

Opening Exercise (0 points)

Discussion (25 points)

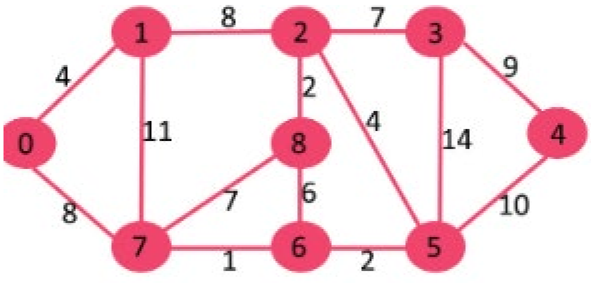
Mastery Exercise (10 points)

Portfolio Project Milestone (150 points)

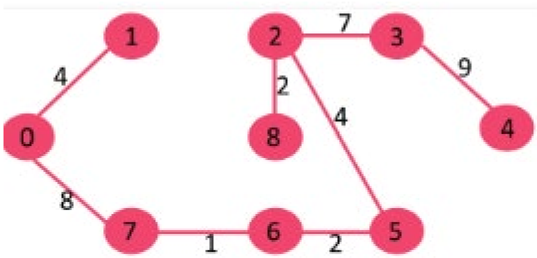
Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Calculate a Robotic Trajectory to Deliver Packages in a Street Network

You are to implement a robotic trajectory program that delivers packages to buildings in a street network. Consider the following street network:



Each filled circle represents a package drop-off location and each link represents a "street." The numbers assigned to the links (edges) represent a "cost" incurred by the robot as is moves along the link (street, edge). For your program, you are tasked with finding the fewest number of streets the robot must traverse to deliver packages to all of the network nodes (buildings). There may be more than one solution, so your program must identify the "subnetwork" or "subgraph" that has the least edge cost. Your program must work for any arbitrary network. The solution for the given network is:



The Java program must be general enough to solve any street. Your instructor will test your program using a different street configuration. Read the street configuration from an input text file located in the same folder as your source file. The final output of your program should be written to a text file in the same folder as your source file. Submit the codes for your program as a text file through the assignment link.

Option 2: Calculate a Robotic Trajectory to Transport Goods

For this Portfolio option you are to write a Java program to calculate a robotic trajectory that meets the following specifications. A robot is used to transport goods where each item has a given weight and monetary value. If you have a list of items and their corresponding weights and values, find the number of each item the robot can transport up to the maximum weight the robot can carry. In addition, the monetary amount of the robot's payload must be as large as possible. Use the following as an example for program inputs and analysis:

value[] = {60,100,120};

weight[] = {10,20,30};

Robot weight capacity = 50;

If the robot carries (lbs):	The value of the payload is ($):
10	60
20	100
30	120
(20 + 10)	(100 + 60)
(30 + 10)	(120 + 60)
(30 + 20)	(120 + 100)
(30 + 20 + 10) -- error > 50	

Use each item only once for a given payload.

Read the input configuration from an input text file located in the same folder as your source file. Your instructor will modify your inputs as part of your program evaluation. The final output should be a description of the optimal load and should be written to a text file in the same folder as your source file. Submit the codes for your program as a text file through the assignment link.

Module 8

Readings

- Chapters 8 & 10 in *Modern Robotics: Mechanics, Planning, and Control*

Opening Exercise (0 points)

Discussion (25 points)

Mastery Exercise (10 points)

Portfolio Project (200 points)

Choose one of the following two assignments to complete this week. Do not do both assignments. Identify your assignment choice in the title of your submission.

Option 1: Trajectory of a Robot Through a Maze

Part 1 – Application (100 points)

In your Portfolio Project, you will write software that plans a trajectory of a robot through a maze. Consider the following problem:

Using the BubbleRob robot in V-Rep (linked in the assignment), you will want to construct an appropriate simulation that will allow for a robot to navigate through a scene that consists of at least three objects. The robot should be able to avoid each of the three objects.

Submit your robot code for your program.

Part 2 - Summary (100 points)

For Part 2, you will provide a detailed overview of the applications of the robot that you have created.

1. What are three scenarios in which the robot could be used to assist with a current problem, such as search and rescue, grocery store stocking, etc.?
2. Identify current limitations in robot technology and theory that might hinder this technology from being used in real life.

Please ensure that your summary is a minimum of two pages in length and includes at least three outside references (not references provided in this course).

Ensure your summary is formatted according to CSU Global APA standards.

Option #2: Trajectory of a Robot Through a Maze (200 points)

Part 1 – Application (100 points)

In your Portfolio Project, you will write software that plans a trajectory of a robot through a maze. Consider the following problem.

Using the BubbleRob robot in V-Rep (linked in assignment), you will want to construct an appropriate simulation that will allow for a robot to navigate through a scene that consists of at least three objects. The robot should be able to avoid each of the three objects.

Submit your robot code for your program.

Part 2 – Slide Presentation Summary (100 points)

In this part, you will provide a detailed overview of the applications of the robot that you have created.

1. What are three scenarios in which the robot could be used to assist with a current problem, such as search and rescue, grocery store stocking, etc.?
2. Identify current limitations in robot technology and theory that might hinder this technology from being used in real life.

Please ensure that your slide presentation is a minimum of 10 slides in length and includes at least three outside references (not references provided in this course).

Ensure your presentation is formatted according to CSU Global APA standards.

Notes for each slide must be provided (50-100 words each slide).

Grading Scale	
A	95.0 – 100
A-	90.0 – 94.9
B+	86.7 – 89.9
B	83.3 – 86.6
B-	80.0 – 83.2
C+	75.0 – 79.9
C	70.0 – 74.9
D	60.0 – 69.9
F	59.9 or below

Course Grading

20% Discussion Participation
0% Opening Exercises
8% Mastery Exercises
37% Critical Thinking Assignments
35% Final Portfolio Project

In-Classroom Policies

For information on late work and incomplete grade policies, please refer to our **In-Classroom Student Policies and Guidelines** or the Academic Catalog for comprehensive documentation of CSU-Global institutional policies.

Academic Integrity
Students must assume responsibility for maintaining honesty in all work submitted for credit and in any other work designated by the instructor of the course. Academic dishonesty includes cheating, fabrication, facilitating academic dishonesty, plagiarism, reusing /re-purposing your own work (see *CSU-Global Guide to Writing and APA Requirements* for percentage of repurposed work that can be used in an assignment), unauthorized possession of academic materials, and unauthorized collaboration. The CSU-Global Library provides information on how students can avoid plagiarism by understanding what it is and how to use the Library and Internet resources.

Citing Sources with APA Style
All students are expected to follow the *CSU-Global Guide to Writing and APA Requirements* when citing in APA (based on the APA Style Manual, 6th edition) for all assignments. For details on CSU-Global APA style, please review the APA resources within the CSU-Global Library under the "APA Guide & Resources" link. A link to this document should also be provided within most assignment descriptions in your course.

Disability Services Statement
CSU–Global is committed to providing reasonable accommodations for all persons with disabilities. Any student with a documented disability requesting academic accommodations should contact the Disability Resource Coordinator at 720-279-0650 and/or email ada@CSUGlobal.edu for additional information to coordinate reasonable accommodations for students with documented disabilities.

Netiquette
Respect the diversity of opinions among the instructor and classmates and engage with them in a courteous, respectful, and professional manner. All posts and classroom communication must be conducted in accordance with the student code of conduct. Think before you push the Send button. Did you say just what you meant? How will the person on the other end read the words?

Maintain an environment free of harassment, stalking, threats, abuse, insults or humiliation toward the instructor and classmates. This includes, but is not limited to, demeaning written or oral comments of an ethnic, religious, age, disability, sexist (or sexual orientation), or racist nature; and the unwanted sexual advances or intimidations by email, or on discussion boards and other postings within or connected to the online classroom. If you have concerns about something that has been said, please let your instructor know.