

LIST OF FIGURES

Figure 2.1 Solution Concept Design	6
Figure 2.2 Function Diagram	7
Figure 2.3 Research by Q.F Zhang and X.Gao [7]	8
Figure 2.4 Research by M. R. Azizi and A. Rastegarpanah [8]	9
Figure 2.5 Robot Mobility With Mecanum Wheel [12]	10
Figure 2.6 Mobile Robot with 4 Mecanum Wheels [11]	10
Figure 2.7 Mecanum Wheel Model [11].....	11
Figure 2.8 Forces and Moments of Forces Acting on the Second and Fourth Mecanum Wheels [13].....	19
Figure 2.9 Forces and Moments of Forces Acting on the First and Third Mecanum Wheels [13].....	19
Figure 2.10 The Force Relationship of the WMR Model [13]	23
Figure 2.11 Unstable System	25
Figure 2.12 Asymptotic Stability	26
Figure 2.13 CLF.....	26
Figure 2.14 CBF.....	27
Figure 2.15 CLBF [5]	29
Figure 2.16 Hybrid Automaton.....	30
Figure 2.17 Hybrid Automaton Illustration	30
Figure 2.18 Initial State and Meeting State.....	31
Figure 2.19 Illustration of AMR Without CLBF Method and Hybrid Automaton.....	32
Figure 2.20 Illustration of AMR With CLBF Method and Hybrid Automaton.....	32
Figure 2.21 Latitude and Longitude [16]	33
Figure 2.22 Direction and Earth Centered Earth Fixed (ECEF) Frame [17]	33
Figure 2.23 Ellipsoidal Coordinates and Satellite Angles [17].....	34
Figure 3.1 Block Diagram.....	35
Figure 3.2 AMR 3D Design Side and Front Views	37
Figure 3.3 AMR 3D Design Back and Top Views	37
Figure 3.4 AMR Schematic Circuit	38
Figure 3.5 3D Plot For Design CLF.....	43
Figure 3.6 Contour Plot For Design CLF	43

Figure 3.7 3D Plot For Design CBF	44
Figure 3.8 Contour Plot For Design CBF	45
Figure 3.9 3D Plot for Design CLBF	45
Figure 3.10 CLBF's relationship with AMR.....	46
Figure 3.11 CLF curves for c_1 and c_2	47
Figure 3.12 CBF curves for c_3 and c_4	47
Figure 3.13 Simulation of the Effect of λ Values	48
Figure 3.14 AMR Against Obstacle.....	48
Figure 3.15 AMR Against Central Coordinates of Unsafe State	49
Figure 3.16 AMR Robot Moves With a Value of $b_i = r$	49
Figure 3.17 AMR Moves to x_e	50
Figure 3.18 Value of $b_i < r$	50
Figure 3.19 Contour Plot For First CLF Waypoint.....	52
Figure 3.20 3D Plot For First CLF Waypoint.....	52
Figure 3.21 Contour Plot For Second CLF Waypoint	53
Figure 3.22 3D Plot For Second CLF Waypoint	53
Figure 3.23 Contour Plot For Third CLF Waypoint	54
Figure 3.24 3D Plot For Third CLF Waypoint	54
Figure 3.25 Value of $\lambda = 50$	58
Figure 3.26 Value of $\lambda = 100$	58
Figure 3.27 Ilustrasion of AMR Against Unsafe State	59
Figure 3.28 Simulation of AMR Toward Waypoint	60
Figure 3.29 Range for Changing Waypoint.....	61
Figure 3.30 Hybrid Automaton Design Schematic	61
Figure 3.31 Flowchart on Simulation Scenario and Data Collection.....	63
Figure 3.32 CLBF Process Flowchart.....	65
Figure 4.1 Error Values of Each RPM.....	70
Figure 4.2 RPM and PWM Graphs For Each Wheel	70
Figure 4.3 Error Values of MPU 6050.....	73
Figure 4.4 Error Values of HC-SR04 Sensor.....	77
Figure 4.5 Graph of Readings For Each Ultrasonic Sensor	77
Figure 4.6 GPS Mapping in the Testing Arena.....	78
Figure 4.7 Error Values of GPS Sensor	80

Figure 4.8 Initial State $x_1 = 18$ and $x_2 = -7$	81
Figure 4.9 Initial State $x_1 = 14$ and $x_2 = -6$	81
Figure 4.10 AMR Simulation With Moving Obstacle	82
Figure 4.11 First Experiment (x_1 Value)	84
Figure 4.12 First Experiment (x_2 Value)	84
Figure 4.13 CLBF Output Value (v_{x_1}) In First Experiment	85
Figure 4.14 CLBF Output Value (v_{x_2}) In First Experiment	85
Figure 4.15 First Experiment (Combined x_1 and x_2 Values)	86
Figure 4.16 AMR Trajectory And Unsafe State In First Experiment	87
Figure 4.17 Euclidian Distance of Moving Obstacles In First Experiment	87
Figure 4.18 Second Experiment (x_1 Value)	88
Figure 4.19 Second Experiment (x_2 Value)	88
Figure 4.20 CLBF Output Value (v_{x_1}) In Second Experiment	89
Figure 4.21 CLBF Output Value (v_{x_2}) In Second Experiment	89
Figure 4.22 Second Experiment (Combined x_1 and x_2 Values)	90
Figure 4.23 AMR Trajectory And Unsafe State In Second Experiment	91
Figure 4.24 Euclidian Distance of Moving Obstacles In Second Experiment	92
Figure 4.25 Third Experiment (x_1 Value)	92
Figure 4.26 Third Experiment (x_2 Value)	93
Figure 4.27 CLBF Output Value (v_{x_1}) In Third Experiment	93
Figure 4.28 CLBF Output Value (v_{x_2}) In Third Experiment	94
Figure 4.29 Third Experiment (Combined x_1 and x_2 Values)	94
Figure 4.30 AMR Trajectory And Unsafe State In Third Experiment	95
Figure 4.31 Euclidian Distance of Moving Obstacles In Third Experiment	96
Figure 4.32 Input and Output Receiver Simulink Circuit	97
Figure A.1 AMR Front View	102
Figure A.2 AMR Side View	102
Figure A.3 Location of Experiment	102