

**DESIGN, TESTING, AND PERFORMANCE OF A HYBRID MICRO  
VEHICLE - THE HOPPING ROTOCHUTE**

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by

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# **DESIGN, TESTING, AND PERFORMANCE OF A HYBRID MICRO VEHICLE - THE HOPPING ROTOCHUTE**

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To my Father, Mother, and Fiancé

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# TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	iv
LIST OF TABLES	ix
LIST OF FIGURES	x
LIST OF SYMBOLS	xv
LIST OF ABBREVIATIONS	xviii
SUMMARY	xix
<u>CHAPTER</u>	
1 INTRODUCTION	1
1.1 Objectives	1
1.2 Robot Locomotion Overview	2
1.3 Existing Hopper Designs	5
1.3.1 JPL Hoppers	5
1.3.2 Jumping Mini-Whegs™	7
1.3.3 Scout	8
1.3.4 Jollbot	9
1.3.5 Glumper	10
1.3.6 Deformable Hoppers	11
1.3.7 Sandia Hoppers	12
1.3.8 Airhoppers	13
1.3.9 Pendulum-Type Hopper	14
1.4 Design Drivers and Rotor Locomotion Selection	16
1.5 Specific System Requirements	18

1.6 Hopping Robot Concept Selection	19
1.7 Contributions of the Thesis	20
1.8 Thesis Outline	20
2 DESIGN OF THE HOPPING ROTOCHUTE	22
2.1 Initial Hopping Rotochute Designs	22
2.2 Hopping Rotochute Components	27
2.2.1 Propulsion System	27
2.2.2 Electronics	31
2.2.3 Main Body	35
2.3 Final Design and Layout	42
3 TESTING OF THE HOPPING ROTOCHUTE PROTOTYPE	46
3.1 Rotor System Aerodynamic Analysis	46
3.2 Flight Testing of the Hopping Rotochute Prototype	52
3.3 Discussion	59
4 HOPPING ROTOCHUTE DYNAMIC MODEL	61
4.1 Equations of Motion	62
4.2 Body Forces and Moments	64
4.3 Discussion	73
5 VALIDATION OF THE DYNAMIC MODEL	74
5.1 Motion Measurement System	74
5.2 Ground Contact Validation	78
5.3 Flight Dynamic Validation	85
6 FLIGHT PERFORMANCE OF THE HOPPING ROTOCHUTE	94
6.1 Example Trajectories	94
6.2 Flight Performance Trade Studies	102



6.3 Atmospheric Wind Trade Studies	117
6.4 Trajectory Shaping	119
7 CONCLUSIONS AND FUTURE WORK	123
7.1 Conclusions	123
7.2 Recommended Future Works	125
APPENDIX A: HOPPING ROTOCHUTE PROTOTYPE FABRICATION	129
APPENDIX B: HOPPING ROTOCHUTE COMPONENT DRAWINGS	132
REFERENCES	137
VITA	147

## LIST OF TABLES

	Page
Table 1.1: Existing hopper design details	15
Table 1.2: Robot locomotion decision matrix	17
Table 2.1: Properties of pre-built micro helicopters	29
Table 2.2: Properties of receivers	31
Table 2.3: Properties of electronic speed controllers	32
Table 2.4: Properties of servos	33
Table 2.5: Properties of batteries	35
Table 2.6: Cushion foam material properties	41
Table 2.7: Mass properties of components	45
Table 5.1: Material properties	80
Table 5.2: Aerodynamic properties	86
Table 6.1: Properties of system 1 and 2	95

## LIST OF FIGURES

	Page
Figure 1.1: First, second, and third generation JPL hoppers	7
Figure 1.2: Jumping Mini-Whegs <sup>TM</sup>	8
Figure 1.3: Scout	9
Figure 1.4: Jollbot	10
Figure 1.5: Glumper	11
Figure 1.6: Deformable hoppers	12
Figure 1.7: Sandia hoppers	13
Figure 1.8: Airhoppers	14
Figure 2.1: First generation Hopping Rotochute conceptual design	23
Figure 2.2: Second generation Hopping Rotochute conceptual design	24
Figure 2.3: Third generation Hopping Rotochute conceptual design	26
Figure 2.4: Fourth generation Hopping Rotochute conceptual design	26
Figure 2.5: Bumble Bee, Leopard, and Reflex micro helicopters	28
Figure 2.6: Modified Reflex rotor system and transmission	30
Figure 2.7: Schematic of transmission	30
Figure 2.8: CIRRUS Micro Joule, CIRRUS MRX-4, and HITEC Micro 05S receivers	31
Figure 2.9: CIRRUS Micro Joule S5A1, CIRRUS Micro Joule S5A2, and Electrify C-7 Nano electronic speed controllers	32
Figure 2.10: CIRRUS CS101/STD Micro, HITEC HS-50 Feather, and HITEC HS-45HB Premium Feather servos	33
Figure 2.11: Apache 250 mAh, Electrify 300 mAh, and Thunder Power 400 mAh batteries	34
Figure 2.12: Hopping Rotochute prototype main body	36

Figure 2.13: Foam cushion force versus deflection	38
Figure 2.14: Drop test stand and model of drop test stand	40
Figure 2.15: Altitude versus time associated with drop test stand	41
Figure 2.16: Hopping Rotochute prototype	43
Figure 2.17: Hopping Rotochute prototype layout	44
Figure 3.1: Rotor test stand	47
Figure 3.2: Rotor thrust versus rotor speed	48
Figure 3.3: Current versus rotor speed	49
Figure 3.4: Potential versus rotor speed	49
Figure 3.5: Power versus rotor speed	50
Figure 3.6: Altitude versus cross range versus range	53
Figure 3.7: Cross range versus range	54
Figure 3.8: Range versus time	54
Figure 3.9: Cross range versus time	55
Figure 3.10: Altitude versus time	55
Figure 3.11: Pitch angle versus time	56
Figure 3.12: Rotor speed versus time	57
Figure 3.13: Thrust versus time	57
Figure 3.14: Current versus time	58
Figure 3.15: Power versus time	58
Figure 4.1: Hopping Rotochute schematic	62
Figure 4.2: Example arrangement of body vertices and ground face for the soft contact model	68
Figure 4.3: Spring and damper schematic for the soft contact model	69
Figure 5.1: Indoor Flight Facility with VICON motion capture system	75
Figure 5.2: Hopping Rotochute prototype with VICON markers	76

Figure 5.3: Polyurethane and carpet spring constants versus vertex spacing	79
Figure 5.4: Altitude versus time associated with drop test stand	81
Figure 5.5: Friction test setup	82
Figure 5.6: Drop test altitude versus time	83
Figure 5.7: Drop test cross range versus range	84
Figure 5.8: Drop test roll angle versus time	84
Figure 5.9: Drop test pitch angle versus time	85
Figure 5.10: Flight test altitude versus cross range versus range	88
Figure 5.11: Flight test range versus time	89
Figure 5.12: Flight test cross range versus time	89
Figure 5.13: Flight test altitude versus time	90
Figure 5.14: Flight test pitch angle versus time	90
Figure 5.15: Flight test forward velocity versus time	91
Figure 5.16: Flight test vertical velocity versus time	91
Figure 5.17: Flight test rotor speed versus time	92
Figure 5.18: Flight test thrust versus time	92
Figure 5.19: Flight test power versus time	93
Figure 6.1: Altitude versus cross range versus range	97
Figure 6.2: Range versus time	98
Figure 6.3: Altitude versus time	98
Figure 6.4: Pitch angle versus time	99
Figure 6.5: Forward velocity versus time	99
Figure 6.6: Vertical velocity versus time	100
Figure 6.7: Rotor speed versus time	100
Figure 6.8: Thrust versus time	101

Figure 6.9: Power versus time	101
Figure 6.10: Current versus time	102
Figure 6.11: Rotor speed profile	103
Figure 6.12: Single hop range versus internal mass offset versus rotor speed using 250 mAh battery	105
Figure 6.13: Launch pitch angle versus internal mass offset using 250 mAh battery	106
Figure 6.14: Maximum altitude versus internal mass offset versus rotor speed using 250 mAh battery	106
Figure 6.15: Number of hops versus rotor speed using 250 mAh battery	107
Figure 6.16: Total range versus internal mass offset versus rotor speed using 250 mAh battery	107
Figure 6.17: Number of hops versus rotor speed using 250, 300, and 480 mAh battery	109
Figure 6.18: Total range versus internal mass offset versus rotor speed using 300 mAh battery	109
Figure 6.19: Maximum altitude versus internal mass offset versus rotor speed using 300 mAh battery	110
Figure 6.20: Total range versus internal mass offset versus rotor speed using 480 mAh battery	111
Figure 6.21: Maximum altitude versus internal mass offset versus rotor speed using 480 mAh battery	111
Figure 6.22: Total range versus internal mass offset versus rotor speed using 250 mAh battery	113
Figure 6.23: Maximum altitude versus internal mass offset versus rotor speed using 250 mAh battery	113
Figure 6.24: Number of hops versus pulse width versus rotor speed using 250 mAh battery	115
Figure 6.25: Total range versus pulse width versus rotor speed using 250 mAh battery	115
Figure 6.26: Maximum altitude versus pulse width versus rotor speed using 250 mAh battery	116

Figure 6.27: Total range versus maximum altitude with 2 s pulse width using 250 mAh battery	117
Figure 6.28: Range versus wind speed	118
Figure 6.29: Wind dispersion	119
Figure 6.30: Altitude versus cross range versus range during trajectory shaping	121
Figure 6.31: Rotor speed versus time during trajectory shaping	121
Figure 6.32: Internal mass angles versus time during trajectory shaping	122
Figure B.1: Main body core	132
Figure B.2: Mounting bracket plate	133
Figure B.3: Mounting bracket pin	133
Figure B.4: Star piece	134
Figure B.5: Lower shaft extension	134
Figure B.6: Transmission mount	135
Figure B.7: Internal mass bar	136
Figure B.8: Internal mass housing	136

## LIST OF SYMBOLS

$c_{1n}, c_{1t}$	normal and tangential damping coefficients associated with body vertices
$c_{2n}, c_{2t}$	normal and tangential damping coefficients associated with ground face
$C_D$	aerodynamic drag coefficient
$C_{lp}, C_{mq}, C_{nr}$	aerodynamic damping moment coefficients in body reference frame
$C_P$	coefficient of power
$C_T$	coefficient of thrust
$d_{IM}$	internal mass offset distance
$D$	aerodynamic reference diameter
$\vec{F}_n, \vec{F}_t$	normal and tangential contact force vectors
$g$	acceleration of gravity
$I$	inertia matrix of Hopping Rotochute about mass center
$k_{1n}, k_{1t}$	normal and tangential spring constants associated with body vertices
$k_{2n}, k_{2t}$	normal and tangential spring constants associated with ground face
$L, M, N$	applied moment components about mass center in body reference frame
$m$	mass of Hopping Rotochute
$\vec{n}$	ground face normal
$p, q, r$	components of angular velocity vector in body reference frame
$\mathbf{R}_{A \rightarrow B}$	skew-symmetric matrix representation of position vector from a generic point $A$ to another point $B$ in body reference frame
$\vec{s}_{1n}, \vec{s}_{1t}$	normal and tangential spring distance vectors associated with body vertices



$\bar{s}_{2n}, \bar{s}_{2t}$	normal and tangential spring distance vectors associated with ground face
$S$	aerodynamic reference area
$SL_{A \rightarrow B}, BL_{A \rightarrow B}, WL_{A \rightarrow B}$	components of position vector from a generic point $A$ to another point $B$ in body reference frame along the stationline, buttline, and waterline
$\mathbf{T}_{BI}$	transformation matrix from inertial reference frame to body reference frame
$\mathbf{T}_{BR}$	transformation matrix from rotor reference frame to body reference frame
$\mathbf{T}_{IB}$	transformation matrix from body reference frame to inertial reference frame
$\mathbf{T}_{PB}$	transformation matrix from body reference frame to internal mass reference
$T$	rotor thrust
$\bar{u}$	absolute velocity of the contact point
$u, v, w$	components of mass center velocity vector in body reference frame
$V_{MW}$	mean atmospheric wind speed
$\bar{w}$	absolute velocity of the surface elements
$x, y, z$	components of mass center position vector in inertial reference frame
$X, Y, Z$	applied force components in body reference frame
$\zeta$	damping ratio
$\theta_{IM}, \psi_{IM}$	internal mass orientation parameters
$\mu$	coefficient of friction
$\rho$	density of air
$\tau$	rotor lag time constant

$\phi, \theta, \psi$	Euler roll, pitch, and yaw angles of Hopping Rotochute
$\phi_F, \theta_F$	filtered Euler roll and pitch angles
$\phi_R, \theta_R$	Euler roll and pitch angles of rotor tip path plane
$\psi_{MW}$	mean atmospheric wind azimuth angle
$\omega_n$	natural frequency

PREVIEW

## LIST OF ABBREVIATIONS

BA	body aerodynamics
C	contact or contact point
CG	center of gravity
CP	center of pressure
DL	disc loading
EPP	expanded polypropylene
EPS	expanded polystyrene
ESC	electronic speed controller
FM	figure of merit
IFF	Indoor Flight Facility
IM	internal mass
MAV	micro air vehicle
MW	mean atmospheric wind
NC	number of contact points
RA	rotor aerodynamics
Rx	receiver
SE	surface element
SMA	shape memory alloy
SR	slow-recovery
W	weight

## SUMMARY

The Hopping Rotochute is a new hybrid micro vehicle that has been developed to robustly explore environments with rough terrain while minimizing energy consumption over long periods of time. The device consists of a small coaxial rotor system housed inside a lightweight cage. The vehicle traverses an area by intermittently powering a small electric motor which drives the rotor system, allowing the vehicle to hop over obstacles of various shapes and sizes. A movable internal mass controls the direction of travel while the egg-like exterior shape and low mass center allows the vehicle to passively reorient itself to an upright attitude when in contact with the ground.

This dissertation presents the design, fabrication, and testing of a radio-controlled Hopping Rotochute prototype as well as an analytical study of the flight performance of the device. The conceptual design iterations are first outlined which were driven by the mission and system requirements assigned to the vehicle. The aerodynamic, mechanical, and electrical design of a prototype is then described, based on the final conceptual design, with particular emphasis on the fundamental trades that must be negotiated for this type of hopping vehicle. The fabrication and testing of this prototype is detailed as well as experimental results obtained from a motion capture system. Basic flight performance of the prototype are reported which demonstrates that the Hopping Rotochute satisfies all appointed system requirements.

A dynamic model of the Hopping Rotochute is also developed in this thesis and employed to predict the flight performance of the vehicle. The dynamic model includes aerodynamic loads from the body and rotor system as well as a soft contact model to

estimate the forces and moments during ground contact. The experimental methods used to estimate the dynamic model parameters are described while comparisons between measured and simulated motion are presented. Good correlation between these motions is shown to validate the dynamic model. Using the validated dynamic model, simulations were performed to better understand the dynamics of the device. In addition, key parameters such as system weight, rotor speed, internal mass weight and location, as well as battery capacity are varied to explore and optimize flight performance characteristics such as single hop height and range, number of hops, and total achievable range. The sensitivity of the Hopping Rotochute to atmospheric winds is also investigated as is the ability of the device to perform trajectory shaping.

# **CHAPTER 1**

## **INTRODUCTION**

Ground and air robots are playing an increasingly important role in many military and civilian systems. An important mission to be tackled by future micro robots is exploring small interior and exterior spaces such as caves, the inside of damaged buildings, and the exterior perimeter of buildings in cluttered urban settings. These environments are commonly characterized by very uneven terrain, highly variable walls, openings, and obstacles. In order to be successful in such rugged environments, the vehicle must be able to robustly traverse the rough terrain in a reliable manner. Besides being mission capable in these difficult environments, future robots will require operations over extended periods of time without being detected. This allows the robot and/or the machine's user to gather as much data as possible during surveillance or reconnaissance missions.

### **1.1 Objectives**

The objective of this thesis was to design and develop a micro robot which can satisfy the mission requirements specified above, namely:

1. The ability to robustly negotiate through and/or over rugged terrain
2. The ability to operate over extended periods of time without being detected

In support of this design, a new hybrid micro robot was invented and a radio-controlled prototype was constructed and subsequently flight tested as a proof-of-concept. Furthermore, a combined flight and ground simulation model was developed to predict and optimize the flight performance of the vehicle.

## 1.2 Robot Locomotion Overview

Many different small and micro robot configurations have been designed, built, tested, and fielded throughout the last few decades including ground, air, and hopping vehicles. These robots, based on different locomotion techniques, possess certain strengths and weaknesses when considering the appointed mission requirements. An overview of these vehicle configurations is given below as well as a discussion of their associated advantages and disadvantages.

The most prevalent type of robot locomotion is based on a wheeled design. Many different types of ground vehicles utilizing wheels have been developed including the four-wheeled MARCbot and the two-wheeled Recon Scout [1, 2]. Although these robots are very efficient at traversing relatively smooth surfaces, they encounter great difficulties when trying to surmount obstacles greater than one-half the diameter of their wheels. Some wheeled robots, such as the Sojourner and Shrimp space rovers, have overcome this limitation by employing bogey systems. These six-wheeled devices are able to climb over obstacles 1.5 and 2 times their wheel diameter respectively [3, 4]. While these vehicles are able to surmount taller obstacles than traditional wheeled robots, they are still limited to overcoming obstruction much less than their overall body length and rely upon many power consuming actuators and complicated suspension systems. Robots of the wheeled type also typically exhibit good maneuverability characteristics allowing them to drive around and avoid challenging terrain. Unfortunately this progress is completely halted when deep gullies, high walls, or other steep terrain are encountered.

Ground vehicles based on a track-type design have also been developed to overcome rough terrain. Two examples are the PackBot and the TALON produced by the iRobot Corporation and Foster-Miller Inc., respectively. The PackBot is equipped with two main treads used for locomotion and two articulated flippers used to climb over obstacles [5]. The vehicle can be driven to speeds up to 2 m/s continuously for 8 hours and can climb up, down, and across surfaces inclined up to 60 deg [6]. The TALON also

consists of two tracks, can travel at speeds up to 2.3 m/s continuously for 4.5 hours, and can maneuver over stairs inclined at 43 deg and side slopes of 45 deg [7]. Although these vehicles can typically outperform similarly sized wheeled robots when traversing rugged terrain, they still possess limitations associated with the maximum obstacle height they can surmount. This maximum height is dependent on several factors including the size of the tracks, the position of the vehicle's mass center, and the friction characteristics between the tread of the track and the terrain. In general, a tracked robot is unlikely to pass over obstacles that are taller than half the vehicle's length unless the mass center is positioned sufficiently far from its geometric center.

Robots utilizing legged locomotion are also better suited for rugged terrain traversal than wheeled vehicles. While these ground vehicles can potentially clamber over very difficult terrain, they are mechanically complex and require numerous joints, actuators, and linkages. In addition, the control of the robot's multiple degrees of freedom requires great computational overhead and power consumption. One such small quadruped robot developed by Boston Dynamics, called LittleDog, is being used by a number of institutions to test control algorithms and has an endurance of 30 min [8, 9]. Some unique "legged" vehicles have been developed which require fewer actuators, such as the RHex and Whegs<sup>TM</sup> which combine the simplicity of wheels with the mobility and adaptability of legs [10 – 12]. Although robots based on a legged design have demonstrated the ability to overcome rugged terrain, it is improbable that they will be able to traverse obstacles taller than double the length of their legs.

The most effective method of traveling over rugged environments is to simply fly above it. Micro air vehicles (MAVs) based on fixed-, rotary-, and flapping-wing designs have been developed which completely avoid obstructions on the ground during the entire mission. The Black Widow developed by AeroVironment, is one such MAV based on a fixed-wing design which is palm-sized, flies at forward speeds of 14 m/s, and has an endurance of around 30 min [13, 14]. The Class I UAV from Honeywell is based on a