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

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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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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
$\mathbf{R}_{A \to B}$	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

$\vec{s}_{2n}, \vec{s}_{2t}$	normal and tangential spring distance vectors associated with ground face
S	aerodynamic reference area
$SL_{A\to B}, BL_{A\to B}, WL_{A\to B}$	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
$\vec{u}$	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
$\vec{w}$	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
ζ	damping ratio
θ_{IM}, ψ_{IM}	internal mass orientation parameters
μ	coefficient of friction
ρ	density of air
τ	rotor lag time constant

ϕ, θ, ψ	Euler roll, pitch, and yaw angles of Hopping Rotochute
ϕ_F, θ_F	filtered Euler roll and pitch angles
ϕ_R, θ_R	Euler roll and pitch angles of rotor tip path plane
ψ_{MW}	mean atmospheric wind azimuth angle
ω_n	natural frequency

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™ 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