AN ABSTRACT OF THE DISSERTATION OF

Danielle Monique Jackson for the degree of Doctor of Philosophy in Mechanical Engineering presented on July 13, 2018.

Title: Bio-Inspired Design of Vehicles that Operate in Complex Environments

Abstract approved:

Dr. Robert B. Stone

This dissertation focuses on defining underlying mechanisms to enable the bio-inspired design of aerodynamic and/or hydrodynamic vehicles that operate within complex environments. This dissertation introduces four overarching research gaps found in current bio-inspired design research and four corresponding approach questions that guide the framework of the presented research. This research addresses the issues of a lack in determining "better" inspirational options for designers to use, a lack of automated methods within the field of bio-inspired design, a lack in a mechanical ranking system that is based on biology, and a lack of focus on capability an mobility linking the bio and mechanical world. This dissertation addresses these gaps through approach questions, used to design an Animal Specification Mobility Analysis (ASMA) methodology. This design methodology guides a designer to a potential bio-inspiration using simulations based on measurable specifications. These specifications help determine a score that represents the functionality of an animal within an environment. These scores supplement rank-able mobility characteristics that mathematically define what an animal may be capable of in terms of movement. The

presented methodology is validated through three types of bio-inspired scenarios, each representing the current types of bio-inspired design processes.

Bio-Inspired Design of Vehicles that Operate in Complex Environments

by
Danielle Monique Jackson

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented July 13, 2018
Commencement June 2019

Doctor of Philosophy dissertation of Danielle Monique Jackson presented on July 13, 2018

APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Danielle Monique Jackson, Author

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. Rob Stone, for giving me this opportunity to continue my education and peruse my interests in design within mechanical engineering.

I would like to thank Dr. Nancy Squires, my professor, my mentor, and my friend for believing in me and guiding me as I strive to become a better engineer.

I would like to thank Dr. Christopher Hoyle for continuing to serve on my graduate committee, throughout my masters and PhD, and for his guidance and patience.

I would like to thank my undergraduate research assistants, Marshall Miller and Brian Johnstone, for their hard work, determination, and patience throughout my project.

I would like to thank my family for their consistent support and faith in my ability to achieve my dreams.

I would like to thank my friends for the wonderful memories that we have made during my academic career and for filling my journey through school with laughter and enjoyment.

CONTRIBUTION OF AUTHORS

Dr. Rob Stone, acting as major professor, oversaw the research and documentation of works provided in this dissertation. Dr. Stone also acted as an editor of the presented work.

Dr. Christopher Hoyle acted as a second advising professor for this research and oversaw the statistical analysis techniques used in this work.

Dr. Nancy Squires oversaw the aerodynamic/hydrodynamic aspect of the presented research, specifically the formulation of the mobility equations used to describe the fluidic movements of animals.

Marshall Miller assisted in the research as an undergraduate research assistant. Marshal aided in both the animal and environment database creation as well as a graphical user interface that may apply to the future work of this research. Marshal also aided in a bio-inspired literature review spanning the last decade.

Brian Johnstone assisted in the research as an undergraduate research assistant. Brian assisted in preliminary research respective to animal joints and modeling approaches, the animal and environmental databases, and the Matlab code presented in this work.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF EQUATIONS

LIST OF EQUATIONS (Continued)

1. Introduction

The research objective of this dissertation is to: *formulate, and validate the steps of a design process to guide designers in selecting possible biological inspirations for a vehicle capable of functioning within a given environment based on a specific mission*.

Biologically inspired, or bio-inspired, design is an approach for biological information, in terms of a concept or component, to be observed and utilized for engineering designs. Bio-inspired design fits within the broader field of design-by-analogy [1]. Bio-inspired engineering design uses analogies from biological systems or phenomena to develop solutions for engineering problems [2]. According to Fu et al., bio-inspired design was established in the field of bionics and biomimetics in the 1950s and has since been used to pull on methods from biology [1].

Biomimetics, or bio-mimicry, is a subset of the larger field of bio-inspired design that addresses the study of mimicking and imitating nature [3]. According to Glier, McAdams, and Linsey, "biomimetic design uses biological phenomena to inspire solutions to engineering problems [4]." During the performed literature review, it became clear that these definitions are not necessarily independent, and in fact it was determined that there is a lack of consensus between the different design processes. To consolidate and clarify these differences we will be using the following distinctions:

> *Biologically-Inspired Design (BID): A design process that seeks a product or system solution to an electromechanical problem and guides the designer to search through biological inspirations that may provide analogies for a portion or the entirety of a concept solution.*

Biomimetic Design: A design process that investigates a biological system, or sub system, and mimics that system physically using electromechanical systems technology to solve a human based problem.

A visual representation of these definitions is presented in Table 1 to help distinguish between the two processes and the steps they include.

Table 1: Bio-Inspired vs. Bio-Mimicry [3]

Bio Inspired	**Bio Mimicry**
From a problem to biology 1. Design problem 2. Search biology 3. Identify applicable inspiration 4. Identify biological function 5. Abstract biological part, whole or concept 6. Evaluate	From biology to an application 1. Biological research 2. Identify biological function 3. Identify application 4. Abstract solution 5. Implement technically 6. Evaluate

In this research effort, we focus on the BID design aspect, particularly for functionality within environments. A designer may implement a BID design process to guide the search through biological organisms to identify feasible biological inspirations.

The ability to design a vehicle to perform to specification within an environment, particularly a complex environment in which the environmental characteristics may have significant effects on vehicles functioning within them, is a key aspect of what this BID method intends to achieve. Achieving desired performance is a paramount concern to designers, particularly when designing for mission specific requirements. A mission statement determines the needs, requirements, and environments concerning a mission.

Returning to the research objective, the expected outcome is a process that results in a logical formation of mechanical designs based on biological organisms. Specifically, to narrow the focus of this research, the chosen organisms will feature various hydrodynamic and/or aerodynamic characteristics.

The approach of this research is to construct a methodology that will guide an engineering designer to create a bio-inspired electromechanical product system that may function within complex environments, as defined by a given mission profile. The process will produce various bio-inspirations based on information collected that concerns the quantifiable aspects of possible mission environments. The research will explore animals that live within the defined environments as well as their mobility functions that help describe the animals and their capabilities based on types of motion. Following the environment and animal search, the animals will be compared against each other to determine how they best fit the needs and requirements of the mission.

Based on the above outline, this research revolves around five critical ideas: i) defining complex environments and exploring the animals that live within them; ii) representing environments and animals with specifications; iii) ranking animals based on maneuverability characteristics; iv) systematically choosing the appropriate animals;

v) and comparing animals and environments to themselves, respectively, to attain similarities.

Currently, as depicted within the literature review below, designers focus on a later optimization approach to biologically inspired design. This process involves choosing a particular organism to mimic or to prompt ideas from, without a clear rationale as to why the organism was chosen in the first place. It appears to be more common practice to choose an organism of interest and apply mechanical mimicry, rather than choose an animal to fit to a specific mission profile.

1.1 Motivation

Biologically inspired design (BID) and the components of such a process are recent research directions and therefore not all well-defined. The driving force behind this research is to address some of these gaps within the BID process and/or the tools used within the process. The significance of this research revolves around four main gaps observed in the review of literature, which are detailed below:

The first gap identified is a *lack of automation in the bio-inspired design process*. It is seen that there was a need for a methodology/tool with an automated component with the intent of helping to streamline the design process and to help users identify and focus on a proper bio-inspiration to solve a problem.

The second area lacking current research methods shows a *missing standard for determining a "better" inspirational source from biology.* There is a need for a methodology that allows a user to design based on measureable biological performance characteristics to attain desired functionality factors.

The third unaddressed issue is *no mechanical ranking system based on biology and the natural world exists*. The need to link the biological and mechanical worlds through measurable, organize-able, and sortable performance attributes.

The forth, and final area unidentified by current research depicts a *lack of focus on capability and mobility linking the bio and mechanical world.* There exists a need for a methodology that links the characteristics of the bio inspiration and the mechanical design in a common language that supports design decision making.

1.2 Background/ Lit Review

The literature review conducted for this research was broken into two separate stages: overall review of subject and specific subjects applied to this particular methodology. This section with feature the information found in the bio-inspired literature review and the project specific topics.

1.2.1 Overall Review

The overall bio-inspired section of the lit review covers topics that were discovered in an evaluation of topics that have been explored during the last decade. Figure 1 displays the main and sub-topics found in this review [5]–[68]. Note that only some of the topics contained subcategories, and I will only be detailing categories that directly relate to this research. These categories include aerodynamics and robotics.

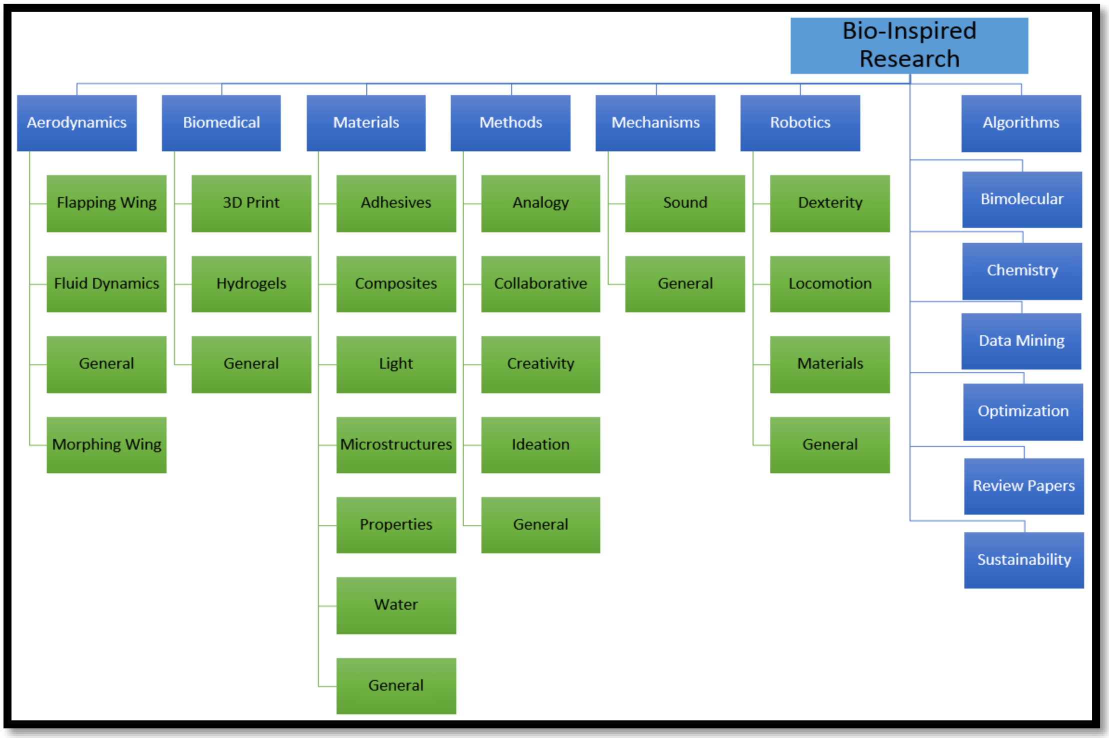


Figure 1: Bio-inspired research review

In the last decade, the topic of bio-inspired aerodynamics was explored and can be divided into the following categories: flapping wings, fluid dynamics, morphing wings, and general design. Within aerodynamics, and the sub category of flapping wings, the research seems to focus around ornithopters. Ornithopters are vehicles that achieve flight by means of a flapping wing design. The research in the literature review shows that work has been done in the field of micro air vehicle [69], the folding and twisting of wing designs [70], and the geometrics of a deployable wing design [71]. Though not related to this research, other research within the topic of flapping wings has pertained to energy harvesting. The second subcategory within aerodynamics is fluid dynamics

[72]. This is important as we must understand how a fluid behaves as it comes in contact with a surface.

The studies presented here implement computational fluid dynamics to determine the flow characteristics about bio inspired surfaces. Both papers explore multiple angles expressed as degrees of freedom or angles of attack [73], [74].

The third subcategory within aerodynamics is morphing wings. The studies conducted within the reviewed papers focus on increasing the performance displayed by aircraft and wind turbines [75]–[77]. It was shown that through the adaptability of a wing via camber and angle of sweep [75], contour wings based on tubercles [76], and wings manufactured from composites capable of aero-elastic behavior [77], prove to be beneficial towards the performance characteristics displayed by wing shapes.

The last two papers reviewed within the aerodynamics category are more general then the others. Both papers focused on bio inspired wing designs. One paper focuses on the design of a robotic bird, specifically a seagull [78]. The paper focuses on the modeling a seagull's wing and how this bird improves its flight performance to achieve steady flight [78]. The second paper focuses on a multi body wings design, in which the multiple bodies are meant to demonstrate the characteristics similar to that of feathers [79].

Robotics is the second category within the larger literature review that will be discussed in further detail due to its strong relatability to this research. Dexterity was the first of the subcategories that was found and it included topics such as modeling a bio inspired condylar joint and determining mechanical advantages based on an offset angle and offset gap within the joint [80]. Other topics included a robotic hand implantation [81] and a bio inspired tendon driven actuation arm with pneumatic components [82].

Locomotion proved to be another important aspect within the research of robotics over the last decade. The movement papers included three that focused on micro robotics [83]–[85] and of the three, two focused on underwater locomotion of walking [83] and swimming [84]. There are also a few papers that discuss the gait of locomotion on a given robot design and how an optimized pattern of movement can be obtained through an increase in velocity and efficiency [86], degree of freedom displayed by the robot [87], and an increase in friction between the surface of the robot and the ground surface [88]. Multimodal motion is also described in a paper that was written around the design of a robot to achieve motion for on land and in water [89]. Locomotion was also researched in terms of fluid movement underwater inspired by an octopus [90]. This research resulted in display of a recovery of fluid energy which was then employed to improve propulsion [90]. The last two papers within this subcategory discuss the modeling approach of a continuous, or rather elongated body, robot with an implemented Newton-Euler algorithm [91] and the postural stabilization and dynamic walking of a humanoid robot [92].

The review on the material aspect of robotics resulted in a few papers. The first paper focuses on a review of soft body robotics and developments made in the field of robotics in terms of decreasing complexities and increasing safety aspects of robots [93]. Another paper discussed the implementation of flexible sharkskin membrane foils with surface denticles to increase the swimming performance under certain scenarios [94]. Finally, the last paper displays experimentally determined friction coefficients, and how a differential friction may provide a forward motion for inchworm like robots [95].

The rest of the papers found in robotics have a wide range of subjects. A couple of papers discusses the modeling, design, and test results of bio inspired robots that have limited mobility of jumping [96], propulsion type for land and water locomotion [97], and limited size robots capable of crawling and rolling movement [98]. The final two papers within this subcategory revolve around novel ideas that incorporate a touch screen controlled 3D biomimetic swimming robotic fish [99], and search methods to explore performance and morphology for collaborative designs between human and machine [100].

1.2.2 Mission Specific Design

Mission design is an important aspect of this project, as this research looks into the design of an aerodynamic and/or hydrodynamic vehicle to function within particular environments. The literature review pertaining to this topic contains information on mission design, design for environments, and will illustrate how a mission is defined.

One of the most well known mission design articles is Space Mission Analysis and Design, written by Wiley J. Larson and James R. Wertz. This text reviews the mission design process, mission characterization, evaluation, as well as specifics in terms of subsystem design, sizing, cost modeling, and even reliability [101]. Larson and Wertz refers to this process as SMAD, and outlines this using major concepts [101]. In particular, the early design phase includes topics such as mission objectives, requirements, and constraints [101]. The authors dictate that the mission environment is a constraint and that the environment is related to product survivability from a mission requirement standpoint [101]. Since the publication of SMAD, others have created add-ons to the design process of SMAD such as software that may support the preliminary analysis for space missions as well as simplify the iterative design concept phase [102].

It is also argued by Bellingham and Rajan that the push to overcome scientific challenges is intertwined with the ability to function within hostile and interdisciplinary environments [103]. These authors also state that the “marine and space environments provide a common motivation to endow robotic platforms with greater onboard autonomy” [103].

1.2.3 Classifying Environments

A review was conducted on classifying environments, resulting in a comparison of methods. Various method types were explored, along with the pros and cons of these methods and obtainable outputs. These papers are discussed below. It should be noted that these documents do not contain or display any equations, as environmental classification is done qualitatively.

Britain’s Habitats: A Guide to the Wildlife Habitats of Britain and Ireland is a document that gives a high level look at primary and secondary habitats [104]. The method employs correspondence tables, however implements combined systems and therefore does not match up well with other similar documents [104]. Three other articles used similar hierarchical or tree diagram frameworks that were created to help users identify habitats [105], make decisions that effected wildlife [106], and facilitate resource management techniques concerning habitats [107]. Another document displayed the use of photo geounit detection which combines a personal interpretational component with landsat imagery [108].

1.2.4 Animal Mobility

The subject of animal mobility encompasses the kinematics and various locomotion aspects of design. In this section, we will present chapters found in a couple of books, which break down the locomotion of animals as well as several papers that focus on animal motion. The books that have been examined are Zoological Physics, written by Boye Ahlborn, and Animal Locomotion, written by Andrew Biewener [45]-[46].

Ahlborn discuses animal locomotion by first introducing the possible forces that an animal or organism might encounter and the internal response necessary to continue to function [109]. It is discussed that that static forces affect the shape and size of an animal and these forces are introduced as forces that are constantly affecting the organism, such as, but not limited to, pressure, friction, and gravity [109]. On the other hand, dynamic forces are forces that act on an organism and appear only when the momentum of an organism is adjusted [109]. Dynamic forces include, but are not limited to, Bernoulli force, lift, drag, and thrust [109]. Ahlborn also talks about evolution and the limitations presented through parameters such as, but not limited to, body mass, speed, frequencies of sound, and temperature [109]. Finally, Ahlborn discussed the kinematics of motion in depth. That is, he displays the equations that illustrate the general principles of linear motion and explains these principles using organism behavior [109].

Unlike Ahlborn, Beiwener discuses animal locomotion in terms of the overarching physical properties of air and water and the dynamic properties that emerge from them [110]. The author initially focuses more within the realm of organisms rather than the engineering aspect of kinematics. Beiwener discuses man-made aerodynamic and hydrodynamic bodies and their differences with biological organisms [110]. Beiwener also discusses the types of flight, and include information on the differences between gliding, soaring, and flapping flight [110].

The physical properties of flapping flight have also been reviewed in a paper that focused on the flight mechanics and control of birds and like sized aircrafts [111]. It was determined that little is known and understood about the mechanics of flapping flight and that there remains to be a lot of unsolved issues within control and stability [111]. Busse et al. discusses a different approach to understanding the kinematics of flapping flight by conducting a 3D study of the wing motion of a particular bat, and focusing on the flapping speed, flexibility, and control parameters [112]. Other research was conducted by Riskin et al., in which the wing deformation of a bat was assets to determine inertial cost on a bat’s flight [113]. Authors Kovacs and Meyers presented work that studied the anatomy, specifically the flight muscles, of the Atlantic Puffin and suggest that the discovered fast-twitch aerobic muscle fibers were a stability variation for wing thrust movement [114]. One other approach used to understand the flight mechanics of birds was introduced by Reynolds, Thomas, and Tayor, where a study was conducted to understand the correlation between atmospheric turbulence and a particular bird’s movement response to the changes in air turbulence [115].

Hydrodynamic performance properties have also been explored in regards to the kinematics of animals. Segre et al. completed a study in which the maneuverability, in terms of roll performance, of a fin whale was predicted using a hydrodynamic model and compared to that of real fin whales [116]. It was determined that the flippers could generate enough lift to allow the whale to achieve a longitudinal-axis roll [116]. Other work has focused on the lift and drag characteristics of cetacean flippers to help determine their performance properties [49]. The aim of the research presented by Weber et al. was to increase the current understanding of factors such as performance, fluid mechanics, and morphology about cetacean flippers, while implementing tools such as computed tomography, and computational fluid dynamics [117]. Other studies have explored the terrestrial locomotion of finned animals and the governing locomotion principles in regards to movement and related body movements [118], [119]. Other authors have investigated mechanized spherical joint systems and the manufacturing of such a devise [120]. Sudki, Lauria, and Noca proposed possible future testing of performance of the devise in terms of propelling forces [120].

1.2.5 Ranking systems

A review was conducted on non-engineering ranking systems, particularly those related to sports, to broaden our view on types of ranking systems that may include components that may be applicable to this research.

The text “Who’s #1?: The Science of Rating and Ranking”, written by Amy Langville and Carl Meyer, discusses several ranking methods, the pros and cons of the detailed methods, and other implemented methods used in parallel [121]. Several of these ranking methods are detailed bellow.

Langville and Meyer present Colley's Method as a ranking system with modifications to winning percentages to allow for the incorporation of strength of schedule to rate the teams [121]. The authors present this as a bias free method that follows a conservation like property, however the method lacks in that it only takes into account the wins or loses of a team [121]. A similar method the authors discuss is Massey's Method, in which the analysis focuses on the performance of a team in terms of the final scores and games played [121]. This method is commonly used to predict the point outcome of a game [121]. Elo's Method, like that of Masseys Method, is used for predictions of wins or loses but is noted that it lacks in predicting past wins and losses, as it becomes more unpredictable when more ratings are used [121]. The method does reward a weaker team for defeating a stronger one and is good at estimating winning percentages [121]. The authors also discuss the Offence-Defense Method, in which offensive and defensive ratings are assigned to each team and used to determine an overall rating for the corresponding teams [121]. This methods is described as easily to implement, however does require some overall knowledge as one set of data will affect the others [121]. Keener's Method is similar to the Offence-Defense method in that one would be relating a rating of a given team to predict an overall strength of that team. Keener's method is depicted as flexible, customizable, and perhaps complex in that it may implement eigenvalues, complex numbers, and negative vales associated negative ratings [121].

1.3 Research Questions/Approach

The content found in the literature review produced an overarching research question in regards to addressing the research gaps within bio-inspired design and the interests of the project. This question is stated as “Can biological information be categorized by performance measures to support the design and functional optimization of vehicles that operate in complex environments?”

It is believed that this question is so broad that it encompasses a scope that may not be possible to completely address within one project, so this complex question may be broken into two refined questions to simplify the research scope. These questions are as follows: “Can animal performance be categorized by an engineering-centric set of vehicle mobility performance measures?” and “Given an environment for a particular mission, how can biological performance be mined to suggest concepts for vehicles?”

The above refined questions are further decomposed to help guide the approach of the research and address the gaps found in the literature review. These approach questions are as follows:

- Can we achieve correlation between environmental specifications and animal specifications?
- Can we achieve a fitness score to represent animals that function within a specified environment?
- Can we produce animal or environmental similarity matrices to compare specification values of animals or environments?

- Can we quantify animal mobility functions as either binary effects or a set of numerical representations?

These approach questions are presented in the following sub-sections along with a corresponding proposed methodology components needed to achieve solutions for the refined and overall research questions.

1.3.1 Can we achieve correlation between environmental specifications and animal specifications?

We will be examining the design process in terms of a mission profile. In any operation, the mission profile should define the location and conditions under which the mission will take place. However, this research will focus on complex environments. To answer the first of the approach questions, we must address what describes and defines a complex environment.

For this project, complex environments will be based on the basic physical factors that describe them and how an environment can be broken into those basic forms. A qualitative approach will be used to determine the various forms and levels that and environment exists within. We will be using a similar method that can be seen in work presented by [104], [106]. The following table, Table 2, displays some of the primary environments and these environments divided into groupings that are more specific.

Table 2: Primary, secondary, and tertiary environments

Primary	Secondary	Tertiary
Terrestrial	Forrest	Woods
		Coniferous Forrest
	Desert	
	Plains	Grasslands
		Tundra
	Polar	
Marine		Deep Ocean
		Estuaries
Freshwater		Rivers/Streams
		Lakes

Using information about individual environments, one can begin to define complex environments based on a combination of physical factors present in secondary or tertiary environments. We will not be using any of the primary environments, as they are too vague and in being so less usable to the designer. Figure 2 shows how these environments may be combined to define a complex environment.

Figure 2: Complex environment creation example [58]–[61]

The goal of this research thrust is to define as many primary environments, secondary environments, and tertiary environments as possible, to define as many complex environments as can be. This number of environments is expected to provide a significant start to building a bio-inspired design database of complex environments.

Also needed is a quantification of these complex environments. Because this research will focus on a quantitative approach, the environments may be described with the following specifications:

- Density of Obstacles
- Length of Obstacles
- Width of Obstacles
- Salt Level
- Density of Fluid
- Pressure
- Fluid Speed ($\dot{m}$)

After defining the complex environments, the next step would be to determine what organisms inhabit each one. For this project, we have stipulated that the organism motivation will be on various birds and sea creatures to focus the project on aero/hydro vehicles. Because of this requirement, the animal candidates may be included, but are not limited to, owls, hawks, whales, manatees, sea turtles, seals, and sea lions.

Animal specification must also be quantified, which will later be analyzed with environmental specifications. The following specifications will be used to describe the animals:

- Length
- Width
- Height
- Weight
- Degree of Freedom
- Range
- Power
- Velocity
- Acceleration

These sets should not be limited and in fact should be created on the bases that more specifications may be added in the future to expand the database.

After their creation, the specifications for both the animals and environments may be correlated in some fashion to show relationships between them. This can be formatted to resemble a HoQ of sorts, specifically the roof of the HoQ, in which a set of engineering specifications (ESs) are compared to one another within that set. This research will implement a similar format, however the ESs will be replaced by environmental and animal specifications that are compared against each other without comparisons against other specifications within their own domain. This means that any environmental specification will not be compared against any other environmental specification, and instead will be compared to every animal specification to explore any relationships that may exist.

It should be noted that within the current table not every cell is occupied. This may suggest that little to no correlation exists between the examined specifications, and in that case the correlation strength would be negligible or nonexistent.

It can also be suggested that this type of correlation matrix maybe used to describe the relationship between specifications in a more qualitative approach [122]. This may also allow for further use in terms of importance to a designer via desired specifications.

1.3.2 Can we achieve a fitness score to represent animals that function within a specified environment?

A fitness score that describes the animal and its function within a specific environment would help a user conclude what animal best suites the mission profile. To achieve the desired fitness scores for different animals we will use an Animal-to-Environment Correlation matrix that will be a derivative of the original correlation matrix, however this matrix may be weight based on user desire. If the user can specify needed vehicle attributes based on the given mission, we can implement these desires as weighted importance factors. Figure 3 displays the matrix operations to achieve an animal fitness score.

$$\begin{array}{cccc} [Animal\ Specifications] & \begin{bmatrix} Animal \\ to \\ Environment \\ Correlation \end{bmatrix} & \begin{bmatrix} Environmental \\ Specifications \end{bmatrix} = & \begin{bmatrix} Animal\ Fitness \\ Score \end{bmatrix} \\ 1\ x\ n & \mathrm{n}\ x\ m & \mathrm{m}\ x\ 1 & 1\ x\ 1 \end{array}$$

Figure 3: How to attain an animal fitness score.

If the user has no specific details in regards to the function of the design and therefore no inputs for the weighted array, an array of ones may be used as a placeholder. You will notice that that end result is a single value, displayed as a one by one array. Because this process will be automated, we can create fitness scores for each animal, regardless of if they are found within the given environment. This will allow for a broader scope and variety of animals to be considered.

1.3.3 Can we produce animal or environmental similarity matrices to compare specification values of animals or environments?

While the main purpose of this methodology is to compare animals versus environments, it is also important to compare animals to one another to be able to rank animals based on needed mission capabilities. One way to demonstrate these animal similarities is by presenting the similarities within a matrix comprised of the original animal specification array and the transpose of that array. This type of matrix, a similarity matrix, and can be defined with the equation, Equation 1:

$$A = S^T B S \tag{1}$$

where A may represent an animal or environment, and B may represent another animal or environment, respectively. It can be said that matrix A is similar to matrix B, through S [123]. The same equation may be expressed as matrices as in Figure 4.

$$\boxed{\begin{array}{ccc} [Animal\ Specifications] & [Animal\ Specifications]^T = & \begin{bmatrix} Animal \\ Simularity \\ Matrix \end{bmatrix} \\ \\ n\ x\ 1 & 1\ x\ n & n\ x\ n \end{array}}$$

Figure 4: Animal similarity matrix example.

An advantage to an automated method such as this would be that we may express every animal and/or every environment in terms of matrices and compare them in terms of the user desired characteristics. To accomplish such a task, the automation system must incorporate a fairly large number of samples of each specification, within defined constraints. The constraints can be determined through literature, and for this research the samples maybe randomly created from an algorithm, to ensure randomness, until a time at which the biological information database can be populated by measurable data through experiments.

1.3.4 Can we quantify animal mobility functions as either binary effects or a set of numerical representors?

Motion can be described as the displacement of an object from a starting point to an end point [109]. Animal movement involves the change in accelerations of various muscles within an animal [109]. This allows an animal to maintain a velocity to displace itself over a distance [109].

Animal mobility characteristics describe the motion capabilities that various animals have, including walking, running, swimming, gliding, grasping, diving, etc. For this research, we will be focusing on motion conducted in the air and water, and therefore we will be using the following animal mobility functions:

- Hover
- Dive
- Glide
- Soaring
- Flapping Flight
- Generated Lift
- Average Travel Distance
- Multi-Function Capability (Air/Water)
- Obstacle Avoidance
- Propulsion

One of the main issues with quantifying these types of characteristic is the transition from biology to mechanics. For example, we, as engineers, must understand what it means in the biological world to “hover” and then use that definition to help guide us to a governing equation that may be used to represent the action or mobility feature in question.

As a binary set we can only distinguish these qualities with a yes or no scenario to represent whether or not the animal we are describing, presents these capabilities or not. A set of numerical representation would be more difficult as we will need to explore the physics that apply to these functions. And while this may be more intrusive, the outcome, if successful, should produce a better understanding of the animal capability and superior animal representation within the proposed method.

1.4 Description of the Remaining Chapters

Chapter 2 details a paper prepared for submission, which depicts how complex environments are determined for the use of this research. This chapter also focuses on how a designer may describe an animal's functionality within an environment, using measurable performance characteristics.

Chapter 3 also details work prepared for journal and/or conference submission. This paper continues the work of the previous one, detailing how a designer might explore environment similarity and how a designer may rank animal functionality within an environment.

Chapter 4, again, continues the previous work. However, unlike the other papers this article describes validation techniques and implements three different scenarios used to determine the functionality of the method described throughout this research.

Chapter 5 reviews the code developed to support the research described in this dissertation, and defines how the code implements functions to achieve the major actions outlined in chapters 2 through 4.

Chapter 6 concludes the dissertation with a summary of the main points and discussions established in the preceding chapters. This chapter outlines the full design process developed in this research and remarks upon results to the research gaps and approach questions outlined for this research.

Chapter 7 focuses on future work that may apply to this research and that may further develop the database resources and supporting code created and used in this work.

**Prepared for submission to: Special Issue “Advances in Biologically Inspired Design”
of journal *Designs***

OBTAINING ENVIRONMENTAL CLASSIFICATIONS AND ANIMAL FITNESS SCORES FOR THE USE OF AERO/HYDRO VEHICLE DESIGN FOR COMPLEX ENVIRONMENTS

Danielle M. Jackson, Marshall R. Miller, Brian A. Johnstone, and Robert B. Stone
Design Engineering Lab
Oregon State University
Corvallis, OR, USA

2. Manuscript 1

2.1 Abstract

The field of or biological inspired design (BID) is a subset of the broader area of design by analogy. Research activity in BID has increased rapidly since its establishment in the 1950s [1]. This paper focuses on defining underlying mechanisms to enable the bio-inspired design of aerodynamic and/or hydrodynamic vehicles that operate within complex environments. This paper introduces two overarching research gaps found in current bio-inspired design research and two corresponding approach questions that guide the framework of the research. This paper addresses the issue of a lack in determining "better" inspirational options for designers to use, as well as addresses the lack of automated methods within the field of bio-inspired design. This paper presents a framework to classify environments and to compare and correlate large, and varying, amounts of data to produce a quantifiable score that may be used to represent animals and their attributes.

2.1 Introduction

Biologically inspired, or bio-inspired, design is an approach for biological information or phenomena to be observed and utilized for engineering designs. Bio-inspired design fits within the broader field of design-by-analogy [1]. Bio-inspired engineering design uses analogies of biological systems to develop solutions for engineering problems [2]. According to Fu et al., bio-inspired design was established in the field of bionics and biomimetics in the 1950s and has since been used to pull on methods from biology [1].

Biomimetics, or bio-mimicry, is a component of bio-inspired design that addresses the study of mimicking and imitating nature [3]. According to Glier, McAdams, and Linsey, “biomimetic design uses biological phenomena to inspire solutions to engineering problems” [4]. During the performed literature review, it became clear that these definitions are not necessarily independent, and, in fact, it was determined that there is a lack of consensus between the different design processes. To consolidate and clarify these differences we will be using the following distinctions:

Biological Inspired Design: A design process that seeks a product or system solution to an electromechanical problem and guides the designer to search through biological inspirations that may provide analogies for a portion or the entirety of a concept solution.

Biomimetic Design: A design process that investigates a biological system, or sub system, and mimics that system physically using electromechanical systems technology to solve a human based problem.

A visual representation of these definitions is presented in the following table, Table 3, to help distinguish between the two processes and the steps they include.

Table 3: Bio-Inspired vs Bio-Mimicry

Bio Inspired	**Bio Mimicry**
From a problem to biology 7. Design problem 8. Search biology 9. Identify applicable inspiration 10. Identify biological function 11. Abstract biological part, whole or concept 12. Evaluate	From biology to an application 7. Biological research 8. Identify biological function 9. Identify application 10. Abstract solution 11. Implement technically 12. Evaluate

For this research, we will focus on the biologically inspired design aspect, particularly for functionality within environments. A designer may implement a biological inspirational design process to guide the search through biological organisms to identify feasible biological inspirations.

The ability to design a vehicle to perform to specification within an environment, particularly a complex environment in which the environmental characteristics may have significant effects on vehicles functioning within them, is a key aspect of what this BID method intends to achieve. Achieving desired performance is a paramount concern to designers, particularly when designing for mission specific requirements. A mission statement determines the needs, requirements, and environments concerning a mission.

Returning to the research objective, the expected outcome is a process that results in a logical formation of electromechanical product and systems designs inspired by biological organisms. Specifically, to narrow the focus of this research, the chosen organisms will feature various hydrodynamic and/or aerodynamic characteristics.

2.2 Motivation

Biologically inspired design (BID) and the components of such a process are recent research directions and therefore not all well-defined. The driving force behind this research is to address several gaps within the generally accepted BID processes and/or tools used within the process. The significance of this research revolves around two main gaps observed in the review of literature, which are detailed below:

BID gap 1: *A lack of automation in the bio-inspired design process.* A need is observed for a methodology/tool with an automated component with the intent of helping to streamline the design process and to help users focus on a proper bio-inspiration to solve a problem.

BID gap 2: *A missing standard for determining a "better" inspirational source from biology.* There is a need for a methodology that allows a user to design based on measureable biological and environmental characteristics to attain desired functionality factors.

2.3 Background/Literature Review

The literature review conducted for this research was broken into two separate stages: overall review of relevant BID subject areas and topics specific to this particular methodology. This section will feature the information found in the bio-inspired literature review and the project specific topics.

2.3.1 Overall Review

The overall bio-inspired section of the lit review covers topics that were discovered in an evaluation of topics that have been explored during the last decade. These categories include aerodynamics, hydrodynamics, and robotics.

In the last decade, the topic of bio-inspired aerodynamics was explored and can be divided into the following categories: flapping wings, fluid dynamics, morphing wings, and general design. Within aerodynamics, and the sub category of flapping wings, the research tends to focus around ornithopters. Ornithopters are vehicles that achieve flight by means of a flapping wing design. The research review shows that work has been done in the field of micro air vehicles [69], the folding and twisting of wing designs [70], and the geometries of a deployable wing design [71]. Though not directly related to this research, other research within the topic of flapping wings has pertained to energy harvesting.

The second subcategory within aerodynamics is fluid dynamics [72]. This is important as we must understand how a fluid behaves as it comes in contact with a surface. The studies presented here implement computational fluid dynamics to determine the flow characteristics about bio inspired surfaces. Both papers explore multiple angles expressed as degrees of freedom or angles of attack [73], [74].

The third subcategory within aerodynamics is morphing wings. The studies conducted within the reviewed papers focus on increasing the performance displayed by aircraft and wind turbines [75]–[77]. It was shown that through the adaptability of a wing via camber and angle of sweep [75], contour wings based on tubercles [76], and wings manufactured from composites, capable of aero-elastic behavior [77], prove to be beneficial towards the performance characteristics displayed by wing shapes.

The last two papers reviewed within the aerodynamics category are more general than the others. Both papers focused on bio-inspired wing designs. One paper focuses on the design of a robotic bird, specifically a seagull [78]. The paper focuses on the modeling of a seagull's wing and how this bird improves its flight performance to achieve steady flight [78]. The second paper focuses on a multi body wing design, in which the multiple bodies are meant to demonstrate the characteristics similar to those of feathers [79].

Robotics is the second category within the larger literature review that will be discussed in further detail due to its strong relatability to this research. Dexterity was the first of the subcategories that was found and it included topics such as modeling a bio inspired condylar joint and determining mechanical advantages based on an offset angle and offset gap within the joint [80]. Other topics included a robotic hand implantation [81] and a bio inspired tendon driven actuation arm with pneumatic components [82].

Locomotion proved to be another important aspect within the research of robotics over the last decade. The locomotion papers included three that focused on micro robotics [83]–[85] and of the three, two focused on underwater locomotion of walking [83] and swimming [84]. There are also a few papers that discuss the gait of locomotion on a given robot design and how an optimized pattern of movement can be obtained through an increase in velocity and efficiency [86], degree of freedom displayed by the robot [87], and an increase in friction between the surface of the robot and ground surface [88]. Multimodal motion is also described in a paper that was written around the design of a robot to achieve motion for both on land and in water [89]. Locomotion was also researched in terms of fluid movement underwater inspired by an octopus [90]. This research resulted in the display of a recovery of fluid energy which was then employed to improve propulsion [90]. The last two papers within this subcategory discuss the modeling approach of a continuous-, or rather elongated-, body robot with an implemented Newton-Euler algorithm [91] and the postural stabilization and dynamic walking of a humanoid robot [92].

In reviewing the material research aspect of robotics, one paper focuses on a review of soft body robotics and developments made in the field of robotics in terms of decreasing complexities and increasing safety aspects of robots [93]. Another paper discusses the implementation of flexible sharkskin membrane foils with surface denticles to increase the swimming performance under certain scenarios [94]. Finally, the last paper displays experimentally determined friction coefficients, and how a differential friction may provide a forward motion for inchworm like robots [95].

The remainder of papers found in bio-inspired robotics cover a wide range of subjects. Some papers discuss the modeling, design, and test results of bio-inspired robots that have limited mobility of jumping [96], propulsion type for land and water locomotion [97], and limited size robots capable of crawling and rolling movement [98]. The final two papers within this subcategory revolve around novel ideas that incorporate a touch screen controlled 3D biomimetic swimming robotic fish [99], and search methods to explore performance and morphology for collaborative designs between human and machine [100].

The information detailed here describes the importance of aerodynamic and robotic research to the bio-inspired design processes. Researchers have shared insights into the functionality and capability of wing and fin design and how, as engineers, we can design mechanisms that may compete with their natural counterparts. These types of research topics all revolve around the "how-to"s of locomotion, which includes both biological and mechanical standpoints on how various types of motion maybe achieved. As stated earlier, the key gap observed is that there is no consistent way in which researchers tried to identify the better or the best biological phenomenon for inspiration.

2.3.2 Mission Specific Design

Mission design is an important aspect of this project, as this research looks into the design of an aerodynamic and/or hydrodynamic vehicle to function within particular environments. The literature review pertaining to this topic contains information on mission design, design for environments, and illustrations of how a mission is defined. One of the most well-known mission design documents is Space Mission Analysis and Design by Larson and Wertz [101]. This text reviews the mission design process, mission characterization and evaluation; as well as specifics in terms of subsystem design, sizing, cost modeling, and even reliability. Larson and Wertz refers to this process as SMAD (taken as the acronym of the text's title), and outlines this using major concepts [101]. In particular, the early design phase includes topics such as mission objectives, requirements, and constraints [101]. The authors dictate that the mission environment is a constraint and that the environment is related to product survivability from a mission requirement standpoint [101]. Since the publication of SMAD, others have created add-ons to the design process of SMAD such as software that may support the preliminary analysis for space missions as well as simplify the iterative design concept phase [102].

It is also argued by Bellingham and Rajan that the push to overcome scientific challenges is intertwined with the ability to function within hostile and interdisciplinary environments [103]. These authors also state that the “marine and space environments provide a common motivation to endow robotic platforms with greater onboard autonomy” [103].

From the information given in this section, it can be seen that there is a critical push towards early design phase techniques and research has focused on mission characteristics with a momentum building towards robotic design programs. It illuminates the aforementioned gap of lacking methods to assist designers in identifying appropriate biological inspirations to operate in given environmental constraints.

2.3.3 Classifying Environments

A review was conducted on classifying environments, resulting in a comparison of methods. Various method types were explored, along with the pros and cons of these methods and obtainable outputs. These papers are discussed below. It should be noted that these documents do not contain or display any equations, as environmental classification tends to be conducted qualitatively. *Britain’s Habitats: A Guide to the Wildlife Habitats of Britain and Ireland* is a document that gives a high level look at primary and secondary habitats using a method which employs correspondence tables, but implements combined systems and therefore does not match up well with other similar documents [104]. Three other articles that used similar hierarchical or tree diagram frameworks that were created to help users identify habitats [105], make decisions that effected wildlife [106] and facilitate resource management techniques concerning habitats [107]. Another document displayed the use of photo geounit detection which combines a personal interpretational component with Landsat imagery [108].

The classifying environments review proved worthwhile, as the research framed the importance of classification structure and how visual aids tools may be used to help guide the documentation of various environments in a way that is neutral in terminology and understanding from both a biological and mechanical standpoint. This review further supports both identified BID research gaps.

2.4 Research Questions/Approach

The content found in the literature review produced an overarching research question in regards to addressing the research gaps within bio-inspired design and the interests of the project. This question is stated as:

> *"Can biological information be categorized by performance measures to support the design and functional optimization of vehicles that operate in complex environments?"*

This rather complex question may be broken into two refined questions to simplify it: *"Can animal performance be categorized by an engineering-centric set of vehicle mobility performance measures?"* and *"Given an environment for a particular mission, how can biological performance be mined to suggest concepts for vehicles?"*

The above refined questions are further decomposed to help guide the approach of the research and address the gaps found in the literature review. These approach questions are as follows:

Can a correlation between environmental specifications and animal specifications be achieved?

Can a fitness score to represent animals that function within a specified environment be acheived?

These approach questions are presented in the following sub-sections along with a corresponding proposed methodology components needed to achieve solutions for the refined and overall research questions.

2.4.1 Can a correlation between environmental specifications and animal specifications be achieved?

This research will be examining the design process in terms of a mission profile. In any operation, the mission profile should define the location and conditions under which the mission will take place. However, this research will focus on complex environments. To answer the first of the approach questions, we must address what describes and defines a complex environment. In this research, complex environments will be based on the basic physical factors that describe them and how an environment can be broken into those basic forms. A qualitative approach was used to determine the various forms and levels that an environment is composed of. We will be using a similar method that can be seen in work presented by [104], [106].

For this work, information about environment types and habitat make-up was gathered and sorted into varying levels of complexity based on internal environmental factors. It was discovered that global environments could be broken into one of three primary environments: terrestrial, freshwater, and marine. These then could be broken into at least 27 secondary and tertiary environments, depending on the overarching definitions of the secondary environments. For example, the secondary environment plains can be broken up into four tertiary environments: grassland, meadow, tundra, and savanna. While each does display varying environmental attributes, they all fall under the category of plains as they all exhibit characteristics such as open fields and sparse obstacles with varying sizes. It is noteworthy to notice that environments such as woods or forests may not be distinguished by the names of the varying trees, as it is more useful to differentiate between the differences of environments such as woods and forests by environment characteristics.

Using information about individual environments, one can begin to define complex environments based on a combination of physical factors present in secondary or tertiary environments. Figure 5 displays a visual representation on how these environments may be combined to define a complex environment.

Figure 5: Complex environment creation example [124]–[127].

It is seen from the visual representations that the resulted complex environments display characteristics of their comprising components. Using such images, visual analysis dictates that complex environments may be further refined and expanded in quantity. To begin to build a bio-inspired design database of complex environments, a goal was established to define as many primary, secondary, tertiary environments as possible.

While visual representation may help produce more complex environments, a need to quantify these environments does exists. Because this research will focus on a quantitative approach, the environments are described with the following specifications in Table 4:

Table 4: Environmental Specifications

Environmental Specifications
• Density of Obstacles • Length of Obstacles • Width of Obstacles • Salt Level • Density of Fluid • Pressure • Fluid Speed

After defining the complex environments, the next step was to determine what organisms inhabit each one. For this work, we have stipulated that the organism inspiration will be drawn only from birds and sea life to focus the project on aero/hydro vehicles. Because of this requirement, examples of the animal candidates initially included are owls, hawks, whales, manatees, sea turtles, seals, and sea lions. Animal specifications must also be quantified to later be analyzed with environmental specifications. The following specifications, listed in Table 5, will be used to describe the animals:

Table 5: Animal Specifications

Animal Specification
• Length
• Width
• Height
• Weight
• Degree of Freedom
• Range
• Power
• Velocity
• Acceleration

These specifications were chosen for two reasons. First, these specifications give general information about animals that detail sizes, motion capability, predicted capable power, velocity, and acceleration data. This type of information may give designers a better understanding of an animal by describing it in a measurable way. Second, these specifications are measureable values that may be used to quantify mobility characteristics of an animal, characteristics that may be seen on force and motion diagrams. These sets should not be considered to be limiting and in fact were created on the basis that more specifications may be added in the future to expand the database.

After their creation, the specifications for both the animals and environments were correlated to show relationships between them. It was determined that this can be formatted to resemble a House of Quality (HoQ) of sorts, specifically the roof of the HoQ, in which a set of engineering specifications (ESs) are compared to one another within that set [128]. However, this type of correlation matrix maybe used to describe the relationship between specifications in a more qualitative approach [122]. Table 10, in the Annex, depicts this HoQ roof style correlation matrix using simulated values for a harp seal living in polar regions about the northern territories of Canada and around Greenland. The values seen within Table 10 in the Annex were produced using average values attained through a review of current documentation and calculations. While this research will implement a similar format to the style of an HoQ, the ESs will be replaced by environmental and animal specifications that are compared against each other without comparisons against other specifications within their own domain. This means that any environmental specification will not be compared against any other environmental specification, and instead will be compared to every animal specification to explore any relationships that may exist. It was determined that the self-correlating factors were not as important at this stage as we are trying to determine the association between an animal and its environment. However, similarity correlations may play a role later on within the research. Table 5 depicts the correlation matrix type that will be used within future work.

2.4.2 Can a fitness score to represent animals that function within a specified environment be achieved?

A fitness score that describes the animal and its function within a specific environment would help a designer conclude what animal best suites the mission profile and thus serve as better biological inspiration. To achieve the desired fitness scores for different animals, this research will implement the use of an Animal-to-Environment Correlation Matrix that will be a derivative of the original correlation matrix, and which may be weighted based on user desires. If the user can specify needed vehicle attributes based on the given mission, these desires can implement as weighted importance factors.

The Animal-to-Environment Correlation Matrix is only one component to achieve an animal fitness score. The other component is comprised of animal and environmental specification values. Due to lacking experimental information, these values will be averages and not necessarily descriptive of any particular animal, organism, or object within its respective category. The animal and environmental specifications will be used in this process to help determine how the animal in question may function within a specific environment. To achieve this, the animal specifications, presented as an array of values, will be altered by the Animal-to-Environment Correlation Matrix, as seen through matrix multiplication. This newly produced matrix will then be multiplied by a set of environmental specifications that reflect the desired environment. This process will produce a one by one matrix, or rather a single value that will represent how well the animal in question functions within the specified environment. Figure 6 below, depicts this process in matrix form.

$$\begin{array}{cccc} [\mathit{Animal\ Specifications}] & \begin{bmatrix}\mathit{Animal}\\ \mathit{to}\\ \mathit{Environment}\\ \mathit{Correlation}\end{bmatrix} & \begin{bmatrix}\mathit{Environmental}\\ \mathit{Specifications}\end{bmatrix} = & \begin{bmatrix}\mathit{Animal\ Fitness}\\ \mathit{Score}\end{bmatrix} \\ 1\ x\ n & \mathrm{n}\ x\ m & \mathrm{m}\ x\ 1 & 1\ x\ 1 \end{array}$$

Figure 6: How to attain an animal fitness score

Because this process will be automated, we can create fitness scores for each animal, regardless of if they are found within the specified environment. This will allow for a broader scope and variety of animals to be considered.

2. 5 Results

There are two main results that were obtained through the process discussed in this paper: environment categorization and a performance score, known as animal fitness, to characterize an animal’s potential as an inspiration for a vehicle.

2.5.1 Environment categorization

First, it was shown that environments can be categorized by primary, secondary, and tertiary components, and that these specified components can be used to describe complex environments. The environment components and complex environments are displayed in Table 6 and Table 7, respectively.

Table 6: Primary, secondary, and tertiary environments

Primary Environments	Secondary Environments	Tertiary Environments
Terrestrial Habitats		
	Forest	
		Rain Forest
		Woods
		Coniferous Forest
	Desert	
	Plains	
		Grassland
		Meadow
		Tundra
		Savanna
	Substrate	
		Mud
		Rocks
		Coral
		Plants
		Sand
	Canyon	
	Coastal	
	Caves/Caverns	
	Mountain	
	Polar	
Fresh Water		
		Rivers/Streams
		Lakes
		Wetlands/Swamps
Marine		
		Deep Ocean
		Open Ocean
		Estuaries

Table 7: Complex environment composition

Environment	**Composition**
Canyon	Desert + Grassland + Cave
Taiga	Polar + Coniferous Forest + Grassland
Reef	Open Ocean + Cave + Coral
Kelp Forest	Deep Ocean + Rain Forest
Wetlands	Lake + Meadow + Woods + Mud
Coastal	Open Ocean + Mountain
Estuaries	Open Ocean +Meadow + Sand + River
Mangroves	Rain Forest + Open Ocean + Rivers
Coniferous Forest	Woods + Woods
Tundra	Polar + Meadow
Seabed	Deep Ocean + Substrate
Riverbed	River + Mud + Rocks + Plants
Polar Oceans	Polar + Open Ocean + Mountain
Underwater Cave	Cave + Deep Ocean + Substrate
Rain Forest	Coniferous Forest + Coniferous Forest

As depicted in Tables 6 and 7, this research has produced 15 complex environments using a selection of 27 environmental composition components as descriptors. It should be noted that none of the primary environments were used as composition components, as they are too vague and in being so, less usable to the designer.

A couple of the complex environments within the table are noteworthy. Frist, the tree intensive environments are interesting because they are composed of the other types of tree environments. For example, a coniferous forest environment is defined as "woods + woods" in the table above. This system was employed to convey the idea that the difference in types of tree environments is based on density of obstacles and obstacle sizing.

Second, it is shown that in several complex environments, the secondary environment “Substrate” is used instead of its tertiary components. It was determined that enough of the tertiary components were used within the complex environment, that was being described, that it was more effective to address those grouped components as a whole instead of individual pieces to maintain simplicity when compiling the information concerning the complex environments.

2.5.2 Geographical Grounding

After the complex environment compositions were completed, a comparison between like environments was conducted. This was done so not to compare different environments, but to compare the same environment in different graphical locations. From this comparison it was determined that there was so much of variation between like environments at different locations that it would benefit the users if a geographical location was specified. For example, the Canyon environment used in the environment composition describes the Grand Canyon specifically. This is not to say that some of the environmental specifications will not be similar to that of other canyons, but rather to distinguish each environment from one another in a more detailed fashion. This will also be beneficial when determining a biological inspiration, as the choices of animals will become more refined. Table 8 details the environments and their geographical locations.

Table 8: Environments and their geographical locations

Environment	Geographical Location
Canyon	Arizona, USA
Taiga	Northern Alaska, USA; Canada
Reef	Puerto Rico; Bahamas
Kelp Forest	Norther and Eastern North Pacific Oceans
Wetlands	Oregon, USA
Coastal	Southern Oregon, USA; North Pacific
Estuaries	Florida, USA
Mangroves	Florida, USA
Coniferous Forest	North America
Tundra	Northern Canada; Greenland
Seabed	Ocean Floor; Varies
Riverbed	Willamette River
Polar Oceans	Northern Atlantic Ocean; Arctic Ocean
Underwater Cave	Mexico
Rain Forest	Oregon, USA

The geographical locations listed in Table 8, demonstrate the beginning of a complex and comprehensive environment mapping structure. In the future, more complex environments may be explored and more geographic sites can be added to help refine the environments and their corresponding specification. This is predicted to better guide a designer towards a more useful bio-inspiration, as more will be known about a vehicle's operating environment.

2.5.3 Fitness scoring

The second main result of the discussed research is that process discussed in this paper resulted in a fitness score being achieved for a specific animal within a specific environment. This was attained using measureable data, obtained though calculations or experimentation. For this paper, an example of a harp seal functioning within a polar environment was used to demonstrate how the fitness scoring system works. Given the information obtained for a harp seal and its corresponding polar environment and through the use of the previously shown fitness factor matrix operations, it was determined that a harp seal has a fitness score of 6073.907. This may be compared to that of other animals and how well they may function in a polar ocean environment. Table 9 displays a selection of animals and their correlated fitness scores that are respective of a polar ocean environment.

Table 9: Animals and their fitness scores in a polar environment

Animal	Fitness Score
Owl	17.993
Eagle	64.391
Orca	15918.276
Penguin	56.220
Frigate	413.326
Seal	6073.907
Stingray	17831.393

As stand-alone quantities, this numbers represent the physical characteristics that the investigated animals may achieve in the chosen working environment that it is projected into, via the correlation matrix. These compared values allow for a designer to better understand how well a possible bio-inspiration may perform in a quantifiable and rank able manner.

2.6 Conclusion

Within this paper, bio-inspired design has been discussed in terms of attaining a more meaningful framework that may guide designers by presenting quantifiable scores that represent the relationship of an animal’s characteristics and the environment in which it is functioning. This paper discussed 4 major gaps found within current bio-inspired research and addressed two of them directly. Within this document, it has been shown that environments may be broken into basic components and then combined to attain complex environments, and that a quantifiable correlation between animals and environments can be achieved. It is important to note that this research is being met with a lack of physical experimental information and therefore data was produced to show a working simulation. Particularly, animal and obstacle sizing was determined using photo imagery, combined with educated interpretations and estimated ratio values. An example was presented using a harp seal as an animal example, and its polar ocean habitat as the environment. Using the method presented in this work, an animal fitness score of 6073.907 was obtained, and may be used to describe how well a harp seal may function within its natural environment.

2.7 Future work

Before addressing the next steps of the research, various animals, and their corresponding specifications, should be further studied in terms of producing various fitness scores. The process of creating fitness scores should be completed by both choosing an environment and scoring the animals that live within it, and by using various animals from different environments. This would allow for refinement of the scoring methodology as well as further understanding the meaning of a particular score.

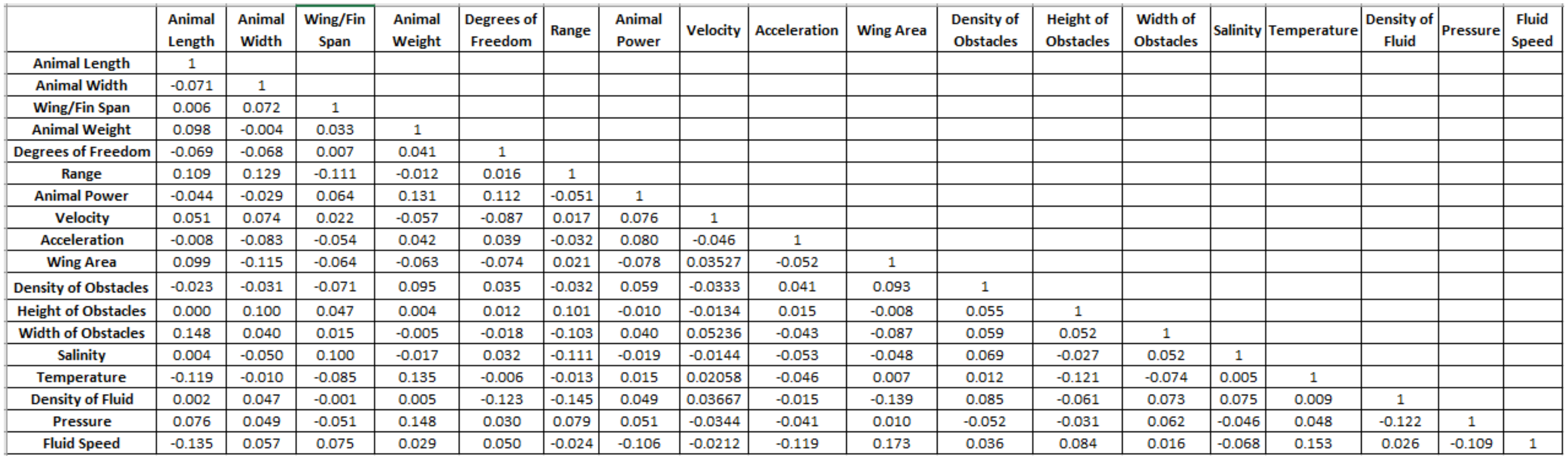
The next steps within the research follow the remaining research approach questions. The first of the remaining questions is “Can we produce animal or environmental similarity matrices to compare specification values of animals or environments?” Since we know that one can obtain a quantifiable correlation between an environment and an animal, it may be assumed that a similarity matrix may be sought after to introduce any correlations between different animals and/or environments, respectively. These similarity matrices may be used to expand a search of possible animal inspirations by exploring comparable environments and the animals that live within them.

The second remaining question is “Can we quantify animal mobility functions as either binary effects or a set of numerical representations?” This question addresses the mobility characteristics that an animal may poses and how we, as designers, might focus on mobility attributes that are deemed desirable.

Annex A

Animal-to-Environment Correlation

Table 10: Animal to Environment Correlation Matrix-HoQ Style

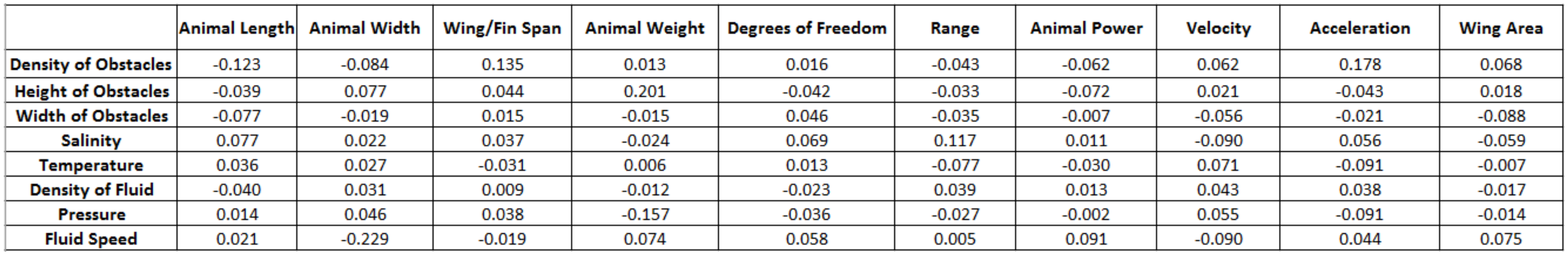


	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area	Density of Obstacles	Height of Obstacles	Width of Obstacles	Salinity	Temperature	Density of Fluid	Pressure	Fluid Speed
Animal Length	1																	
Animal Width	-0.071	1																
Wing/Fin Span	0.006	0.072	1															
Animal Weight	0.098	-0.004	0.033	1														
Degrees of Freedom	-0.069	-0.068	0.007	0.041	1													
Range	0.109	0.129	-0.111	-0.012	0.016	1												
Animal Power	-0.044	-0.029	0.064	0.131	0.112	-0.051	1											
Velocity	0.051	0.074	0.022	-0.057	-0.087	0.017	0.076	1										
Acceleration	-0.008	-0.083	-0.054	0.042	0.039	-0.032	0.080	-0.046	1									
Wing Area	0.099	-0.115	-0.064	-0.063	-0.074	0.021	-0.078	0.03527	-0.052	1								
Density of Obstacles	-0.023	-0.031	-0.071	0.095	0.035	-0.032	0.059	-0.0333	0.041	0.093	1							
Height of Obstacles	0.000	0.100	0.047	0.004	0.012	0.101	-0.010	-0.0134	0.015	-0.008	0.055	1						
Width of Obstacles	0.148	0.040	0.015	-0.005	-0.018	-0.103	0.040	0.05236	-0.043	-0.087	0.059	0.052	1					
Salinity	0.004	-0.050	0.100	-0.017	0.032	-0.111	-0.019	-0.0144	-0.053	-0.048	0.069	-0.027	0.052	1				
Temperature	-0.119	-0.010	-0.085	0.135	-0.006	-0.013	0.015	0.02058	-0.046	0.007	0.012	-0.121	-0.074	0.005	1			
Density of Fluid	0.002	0.047	-0.001	0.005	-0.123	-0.145	0.049	0.03667	-0.015	-0.139	0.085	-0.061	0.073	0.075	0.009	1		
Pressure	0.076	0.049	-0.051	0.148	0.030	0.079	0.051	-0.0344	-0.041	0.010	-0.052	-0.031	0.062	-0.046	0.048	-0.122	1	
Fluid Speed	-0.135	0.057	0.075	0.029	0.050	-0.024	-0.106	-0.0212	-0.119	0.173	0.036	0.084	0.016	-0.068	0.153	0.026	-0.109	1

Annex B

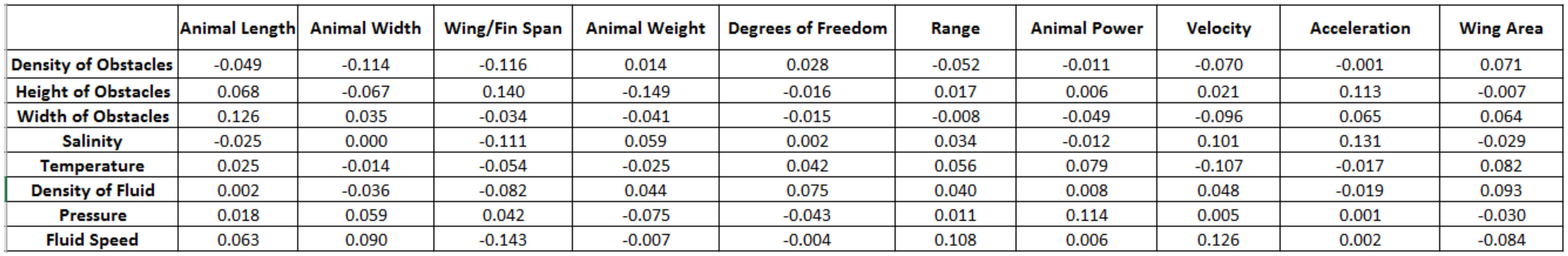
Animal-to-Environment Correlation

Table 11: Owl vs Polar Ocean Correlation Matrix



	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	-0.123	-0.084	0.135	0.013	0.016	-0.043	-0.062	0.062	0.178	0.068
Height of Obstacles	-0.039	0.077	0.044	0.201	-0.042	-0.033	-0.072	0.021	-0.043	0.018
Width of Obstacles	-0.077	-0.019	0.015	-0.015	0.046	-0.035	-0.007	-0.056	-0.021	-0.088
Salinity	0.077	0.022	0.037	-0.024	0.069	0.117	0.011	-0.090	0.056	-0.059
Temperature	0.036	0.027	-0.031	0.006	0.013	-0.077	-0.030	0.071	-0.091	-0.007
Density of Fluid	-0.040	0.031	0.009	-0.012	-0.023	0.039	0.013	0.043	0.038	-0.017
Pressure	0.014	0.046	0.038	-0.157	-0.036	-0.027	-0.002	0.055	-0.091	-0.014
Fluid Speed	0.021	-0.229	-0.019	0.074	0.058	0.005	0.091	-0.090	0.044	0.075

Table 12: Eagle vs Polar Ocean Correlation Matrix



	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	-0.049	-0.114	-0.116	0.014	0.028	-0.052	-0.011	-0.070	-0.001	0.071
Height of Obstacles	0.068	-0.067	0.140	-0.149	-0.016	0.017	0.006	0.021	0.113	-0.007
Width of Obstacles	0.126	0.035	-0.034	-0.041	-0.015	-0.008	-0.049	-0.096	0.065	0.064
Salinity	-0.025	0.000	-0.111	0.059	0.002	0.034	-0.012	0.101	0.131	-0.029
Temperature	0.025	-0.014	-0.054	-0.025	0.042	0.056	0.079	-0.107	-0.017	0.082
Density of Fluid	0.002	-0.036	-0.082	0.044	0.075	0.040	0.008	0.048	-0.019	0.093
Pressure	0.018	0.059	0.042	-0.075	-0.043	0.011	0.114	0.005	0.001	-0.030
Fluid Speed	0.063	0.090	-0.143	-0.007	-0.004	0.108	0.006	0.126	0.002	-0.084

Annex B (Continued)

Animal-to-Environment Correlation

Table 13: Orca vs Polar Ocean Correlation Matrix

	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	-0.019	-0.040	0.100	-0.059	0.100	0.100	0.035	0.061	-0.047	0.008
Height of Obstacles	-0.037	0.072	0.062	0.050	-0.027	-0.033	-0.053	0.073	0.014	0.092
Width of Obstacles	-0.001	-0.018	-0.029	-0.070	0.092	-0.091	-0.022	0.093	-0.121	0.135
Salinity	0.118	0.065	-0.026	0.002	0.012	-0.031	-0.048	-0.048	0.121	-0.033
Temperature	0.061	0.003	0.030	-0.070	0.024	-0.072	-0.001	-0.006	-0.045	0.133
Density of Fluid	0.111	0.077	0.037	-0.084	-0.021	-0.148	0.036	-0.147	0.029	0.108
Pressure	0.049	-0.029	0.065	-0.112	0.056	0.008	-0.011	0.011	0.007	-0.116
Fluid Speed	-0.129	-0.043	0.008	0.006	-0.046	0.054	-0.152	-0.007	-0.036	-0.044

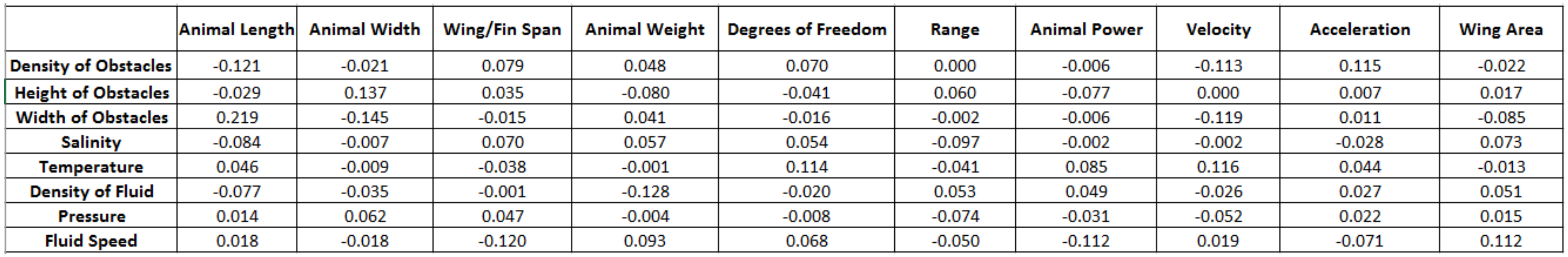
Table 14: Penguin vs Polar Ocean Correlation Matrix

	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	0.110	0.066	0.014	0.111	-0.030	0.070	0.014	-0.030	0.058	0.016
Height of Obstacles	0.022	0.014	0.031	0.000	-0.112	-0.034	0.031	0.015	-0.039	-0.049
Width of Obstacles	-0.053	0.028	-0.026	0.098	0.110	0.112	-0.050	-0.003	0.024	-0.004
Salinity	-0.041	-0.083	-0.028	-0.018	0.151	0.065	-0.005	0.009	-0.035	0.047
Temperature	-0.006	0.096	0.100	0.033	-0.036	0.034	0.042	-0.032	-0.111	0.100
Density of Fluid	0.057	0.002	0.008	-0.124	0.105	-0.109	0.043	0.075	-0.039	0.067
Pressure	0.080	-0.047	-0.035	0.035	-0.094	0.132	-0.012	-0.069	-0.090	0.092
Fluid Speed	-0.134	-0.048	0.083	0.000	-0.006	-0.067	-0.009	-0.180	0.016	0.054

Annex B (Continued)

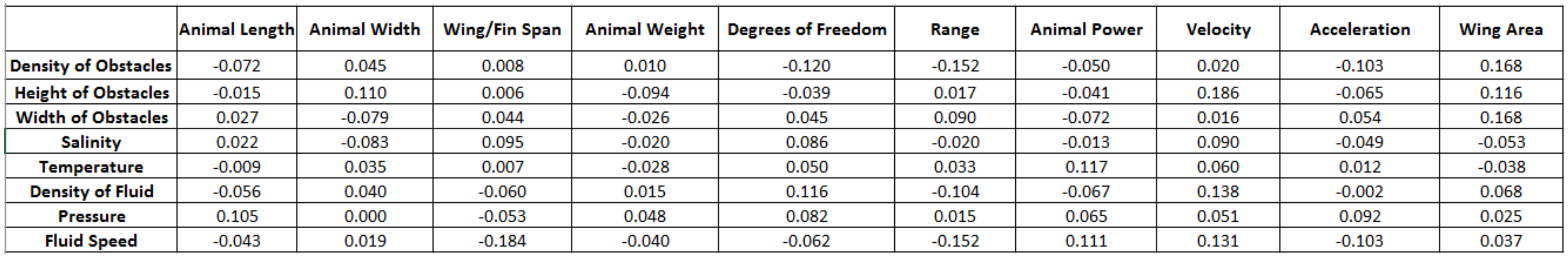
Animal-to-Environment Correlation

Table 15: Frigate Bird vs Polar Ocean Correlation Matrix



	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	-0.121	-0.021	0.079	0.048	0.070	0.000	-0.006	-0.113	0.115	-0.022
Height of Obstacles	-0.029	0.137	0.035	-0.080	-0.041	0.060	-0.077	0.000	0.007	0.017
Width of Obstacles	0.219	-0.145	-0.015	0.041	-0.016	-0.002	-0.006	-0.119	0.011	-0.085
Salinity	-0.084	-0.007	0.070	0.057	0.054	-0.097	-0.002	-0.002	-0.028	0.073
Temperature	0.046	-0.009	-0.038	-0.001	0.114	-0.041	0.085	0.116	0.044	-0.013
Density of Fluid	-0.077	-0.035	-0.001	-0.128	-0.020	0.053	0.049	-0.026	0.027	0.051
Pressure	0.014	0.062	0.047	-0.004	-0.008	-0.074	-0.031	-0.052	0.022	0.015
Fluid Speed	0.018	-0.018	-0.120	0.093	0.068	-0.050	-0.112	0.019	-0.071	0.112

Table 16: Harp Seal vs Polar Ocean Correlation Matrix

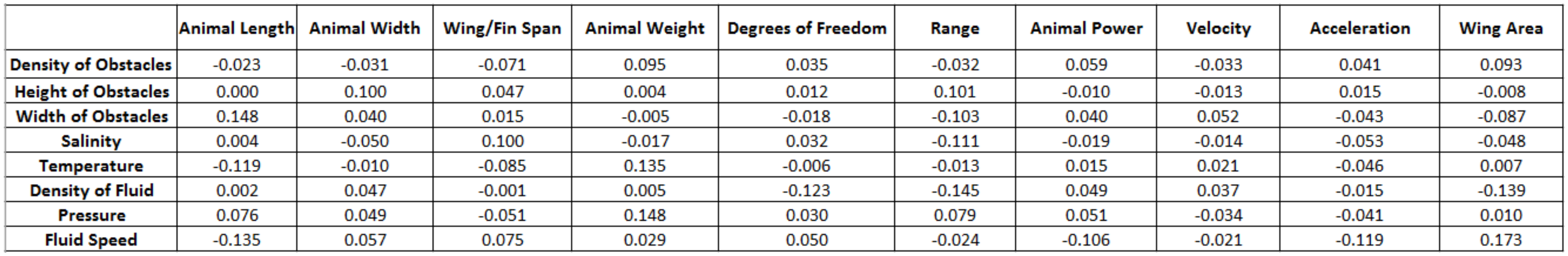


	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	-0.072	0.045	0.008	0.010	-0.120	-0.152	-0.050	0.020	-0.103	0.168
Height of Obstacles	-0.015	0.110	0.006	-0.094	-0.039	0.017	-0.041	0.186	-0.065	0.116
Width of Obstacles	0.027	-0.079	0.044	-0.026	0.045	0.090	-0.072	0.016	0.054	0.168
Salinity	0.022	-0.083	0.095	-0.020	0.086	-0.020	-0.013	0.090	-0.049	-0.053
Temperature	-0.009	0.035	0.007	-0.028	0.050	0.033	0.117	0.060	0.012	-0.038
Density of Fluid	-0.056	0.040	-0.060	0.015	0.116	-0.104	-0.067	0.138	-0.002	0.068
Pressure	0.105	0.000	-0.053	0.048	0.082	0.015	0.065	0.051	0.092	0.025
Fluid Speed	-0.043	0.019	-0.184	-0.040	-0.062	-0.152	0.111	0.131	-0.103	0.037

Annex B (Continued)

Animal-to-Environment Correlation

Table 17: Stingray vs Polar Ocean Correlation Matrix



	Animal Length	Animal Width	Wing/Fin Span	Animal Weight	Degrees of Freedom	Range	Animal Power	Velocity	Acceleration	Wing Area
Density of Obstacles	-0.023	-0.031	-0.071	0.095	0.035	-0.032	0.059	-0.033	0.041	0.093
Height of Obstacles	0.000	0.100	0.047	0.004	0.012	0.101	-0.010	-0.013	0.015	-0.008
Width of Obstacles	0.148	0.040	0.015	-0.005	-0.018	-0.103	0.040	0.052	-0.043	-0.087
Salinity	0.004	-0.050	0.100	-0.017	0.032	-0.111	-0.019	-0.014	-0.053	-0.048
Temperature	-0.119	-0.010	-0.085	0.135	-0.006	-0.013	0.015	0.021	-0.046	0.007
Density of Fluid	0.002	0.047	-0.001	0.005	-0.123	-0.145	0.049	0.037	-0.015	-0.139
Pressure	0.076	0.049	-0.051	0.148	0.030	0.079	0.051	-0.034	-0.041	0.010
Fluid Speed	-0.135	0.057	0.075	0.029	0.050	-0.024	-0.106	-0.021	-0.119	0.173

Proceedings of the ASME 2019 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conferences
IDETC/CIE 2019

PRODUCING ANIMAL AND ENVIRONMETAL SIMILARITY MATRICES AND QUANTIFIABLE ANIMAL MOBILITY FUNCTIONS FOR AN AERO/HYDRO BIO-INSPIRED VEHICLE DESIGN

Danielle M. Jackson, Marshall R. Miller, Brian A. Johnstone, Dr. Christopher Hoyle, and Robert B. Stone
Design Engineering Lab
Oregon State University
Corvallis, OR, USA

3. Manuscript 2

3.1 Abstract

This paper identifies four research gaps within the field of bio-inspired design as it pertains to identifying suitable animals to inspire vehicle design. The gaps are addressed with the proposed design methodology that introduces an automated process that directs the designer towards an animal choice that may be more beneficial for a specified environment based on a mobility characteristic calculation and a ranking system. The ranking system described in this paper is supplemented with a Monte Carlo statistical analysis, in which each described mobility characteristic is calculated for a sample size of 100,000. An example involving the comparison of a harp seal to six other animals in reference to a polar ocean environment is presented and results in a determination that other animals may produce better inspirational sources based on a comparison of environmental and animal specifications and calculated mobility characteristics. These results are displayed as normalized values to assist designers in interpreting them.

3.2 Introduction

Bio-inspired (BID) design is a design approach, within the studies of design by analogy, that utilizes biological information and phenomena to develop engineering designs [1]. The BID approach employs analogies from biology to obtain answers to engineering problems [69].

Where BID focuses on guiding a designer using ideas or concepts found in nature, biomimetic design addresses the process of directly mimicking a system or subsystem found in nature with a mechanical analog [70]. Examples of biomimicry designs include robotic stingrays, robotic geckos, and robotic birds[129]–[131].

This research focuses on the biological inspiration aspect of design, and serves to motivate further work into correlations between environmental conditions and animal mobility characteristics that could inspire a product's design.

Specifically, this paper reports on the research into animal and environmental classifications and how these may help designers engineer aero/hydro vehicles [132]. Previous work explored a method to define complex environments and animal fitness scores describing how an animal may function within an environment [132]. This paper implements the animal fitness scores into a ranking system that focuses on each chosen animal within a specified complex environment.

3.3 Motivation

The motivating influence for this research is to tackle several research gaps found within topics of BID. This research and the implemented process now focuses on four main gaps observed in the review of literature, which are detailed below:

"BID gap 1: *A lack of automation in the bio-inspired design process.* A need exists for a methodology that supports automation in identifying proper bio-inspiration phenomena to solve a problem in order to streamline the design process and create a focused search strategy for the designer" [132].

"BID gap 2: *A missing standard for determining a "better" inspirational source from biology.* There is a need for a methodology that allows a user to design based on measureable biological characteristics to attain desired functionality factors" [132].

BID gap 3: *There is no mechanical ranking system based on biology and the natural world.* The need exists to link the biological and mechanical worlds through measurable, organize-able, and sortable characteristics.

BID gap 4: *A lack of focus on capability and mobility linking the bio and mechanical world exists.* Designers need a methodology that focuses on the biological characteristics of both the bio-inspiration and the mechanical design.

The first and second research gaps listed above are directly addressed in [132] and are supplemented as well as furthered in this work, in which BID gaps three and four are presented and help to tie together the needs that designers have and a methodology to address those needs.

3.4 Background

The literature review conducted for this research is organized in two themes: the overall review of bio-inspired design subjects and specific quantitative subjects that support the particular methodology in this paper. This section will feature the information found in the bio-inspired literature review and the project specific topics.

3.4.1 Bio-inspired Design Overview

This section will discuss an overview of current work in the field of bio-inspired design, specifically the topic of locomotion, which is relevant to the presented work, and previous work done in relation to the work presented in this paper.

Locomotion in BID

Locomotion, as seen through the study of bio-inspired design, has been growing throughout the last decade, particularly in the domain of robotics. The work done, concerning motion, focused on a variety of topics. Several papers focused on micro robotics, while others leaned toward underwater movements[83]–[85]. Other works described the stabilization and dynamic walking ability of humanoid robots [92].

The topic of locomotion was also described in specific movements as seen in dexterity research. Research on dexterity, within robotics, focused on topics such as modeling bio-inspired condylar joints, robotic hand implants, and tendon driven actuation through the use of pneumatic components [80], [81], [83].

Previous Work

This subsection will detail a synopsis of previous work done for this project. The work discussed is from an article prepared for publication, with a focus on describing an animal's functionality within a complex environment [132]. The complex environments were determined through qualitative analysis of environmental components and the functionality descriptor, or fitness score, is determined by relating, through multiplication, specifications from specific animals and environments through a correlation matrix [132]. This correlation matrix uses the specification values and determines a correlation strength for the comparison of each component to another [132]. The fitness score is depicted in Figure 7 below:

$$\begin{bmatrix} Animal \\ Specifications \\ (1\ x\ N) \end{bmatrix} \begin{bmatrix} Animal \\ to \\ Environment \\ Correlation \\ Matrix \\ (N\ x\ M) \end{bmatrix} \begin{bmatrix} Environmental \\ Specifications \\ (M\ x\ 1) \end{bmatrix} = \begin{bmatrix} Animal \\ Fitness \\ Score \\ (1\ x\ 1) \end{bmatrix}$$

Figure 7: Matrix Operation: Animal Fitness Score

The fitness score will be a single value used to help rank an animal's functionality within a particular environment by describing the relationship between the animal and environment specification values.

3.4.2 Animal Mobility

The subject of animal mobility encompasses the kinematics and various locomotion aspects of design. In this section, we will present chapters found in two biological texts which break down the locomotion of animals as well as several papers that focus on animal motion. The texts that have been examined are *Zoological Physics*, written by Boye Ahlborn, and *Animal Locomotion*, written by Andrew Biewener.

Ahlborn discuses animal locomotion by first introducing the possible forces that an animal or organism might encounter and the internal response necessary to continue to function [109]. It is discussed that the static loading affects the shape and size of an animal and these forces include are introduced as forces that are constantly affecting the organism, such as, but not limited to, pressure, friction, and gravity [109]. On the other hand, dynamic forces are forces that act on an organism and appear only when the momentum of an organism is adjusted [109]. Dynamic forces include, but are not limited to, Bernoulli force, lift, drag, and thrust [109]. Ahlborn also talks about evolution and the limitations presented through parameters such as, but not limited to, body mass, speed, frequencies of sound, and temperature [109]. Finally, Ahlborn discussed the kinematics of motion in depth. That is, he displays the equations that illustrate the general principles of motion and explains these principles using organism behavior [109].

Unlike Ahlborn, Beiwener discuses animal locomotion in terms of the overarching physical properties of air and water and the dynamic properties that emerge from them [110]. The author initially focuses more within the realm of organisms rather than the engineering aspect of kinematics. Beiwener discuses man-made aerodynamic and hydrodynamic bodies and their differences with biological organisms [110]. Beiwener also discusses the types of flight, and include information on the differences between gliding, soaring, and flapping flight [110].

The physical properties of flapping flight have also been reviewed in a paper that focused on the flight mechanics and control of birds and like sized aircrafts [111]. It was determined that little is known and understood about the mechanics of flapping flight and that there remains to be a lot of unsolved issues within control and stability [111]. Busse et al. discusses a different approach to understanding the kinematics of flapping flight by conducting a 3D study of the wing motion of a particular bat, and focusing on the flapping speed, flexibility, and control parameters [112]. Other research was conducted by Riskin et al., in which the wing deformation of a bat was assets to determine inertial cost on a bat’s flight [113]. Authors Kovacs and Meyers presented work that studied the anatomy, specifically the flight muscles, of the Atlantic Puffin and suggest that the discovered fast-twitch aerobic muscle fibers were a stability variation for wing thrust movement [114]. One other approach used to understand the flight mechanics of birds was introduced by Reynolds, Thomas, and Tayor, where a study was conducted to understand the correlation between atmospheric turbulence and a particular bird's movement response to the changes in air turbulence [115].

Hydrodynamic performance properties have also been explored in regards to the kinematics of animals. Segre et al. completed a study in which the maneuverability, in terms of roll performance, of a fin whale was predicted using a hydrodynamic model and compared to that of real fin whales [116]. It was determined that the flippers could generate enough lift to allow the whale to achieve a longitudinal-axis roll [116]. Other work has focused on the lift and drag characteristics of cetacean flippers to help determine their performance properties [49]. The aim of the research presented by Weber et al. was to increase the current understanding of factors such as performance, fluid mechanics, and morphology about cetacean flippers, while implementing tools such as computed tomography, and computational fluid dynamics [117]. Other studies have explored the terrestrial locomotion of finned animals and the governing locomotion principles in regards to movement and related body movements [118], [119]. Other authors have investigated mechanized spherical joint systems and the manufacturing of such a devise [120]. Sudki, Lauria, and Noca proposed possible future testing of performance of the devise in terms of propelling forces [120].

The papers discussed within this literature review have highlighted different aspects of mobility in terms of animals, relevant forces, stability, and maneuverability. This set of authors discussed mobility in terms of aero and hydro dynamics, relating kinematic forces and performance requirements.

Measuring Similarity in Design

Two review papers were studied, of which displayed the use of correlation matrices paired with statistical and/or algebraic, geometric, trigonometric based analysis. Steiger discusses the composing of correlation matrix elements focused on population and displayed as a covariance matrix [133]. The author discusses methods to assess two dependent correlations as well as several dependent correlations [133]. Steiger also discussed statistical analysis techniques that may not be beneficial for the use of comparing elements of a correlation matrix [133]. Within the other review paper the authors, Rodgers and Nicewander, discuss 13 conceptual and computational definitions of the correlation coefficient index, used to measure the strength of the correlation [134].

Other work has been done on correlation matrices that involve individual variables and the correlation coefficients produced from the matrix. Dziuban and Shirkey focus on the adequacy of measuring samples to make decisions about individual variables within covariance matrices [135]. The authors also focused on implementing the Bartlett test to simplify assumptions and needs for further statistical tests [135]. Unlike the previously mentioned authors, Lapointe and Legendre implemented a Pearson cross product method to measure distance matrices and a one tailed test for path length statistical analysis [136].

Other work involving similarity and correlation matrices span a wide range of fields and disciplines. Higgins and Sharp explore similarity matrix scores between pairs of progressively aligning sequences using a rescaled Dayhoff method and phylogenetic tree and the weakness of implementing a time consuming technique [137]. Cooper and Foote investigate a process to automatically extract summary excerpts from video and audio files to determine and quantify the maximum similarity, which they produced using a self-similarity matrix process [138]. They focused on minimizing assumptions and inter-frame similarity [138]. Levin, Robson, and Garnier worked on a prediction algorithm using comparisons made with structure assignments of Kabsch and Sander from X-ray data, which employed a sequence similarity score and a pattern recognition process [139]. Wu, Chang, Zhang examined an analytical framework for the analysis of Kernel Machines using cross similarity matrices, linear relationships, embedding data instances, and searching for local solutions [140]. Finally, Higham studied the methodology to find the nearest symmetric positive semidefinite matrix with a unit diagonal by implementing correlation matrices with many zero or negative eigenvalues, which produced a method weakness of a linear convergence rate [141].

In regards to similarity within design, the papers discussed in this section depict a wide variety of similarity modeling uses, particularity within simulations and work focused on information extraction. Several of the documents also reported working towards limiting assumption usage within the respective projects.

3.4.3 Ranking Systems

Ranking systems were explored in various fields of studies. These ranking systems include work on fuzzy numbers, efficiency to sift data, and ranking different types of information. These systems are discussed here.

Chen discusses the decision making process with the inclusion of vague data and inadequate models [142]. Chen uses closeness coefficients and displays a ranking model that uses the distances to fuzzy positive-ideal and negative-ideal solutions [142]. The author focuses on personal selection problems with a solution structured around a hierarchical assembly and a decision matrix [142]. Like Chen, other authors focused on the ranking of fuzzy numbers, specifically numbers with a trapezoidal structure [143]. Ezzati et. al. focused on the symmetry of fuzzy numbers and demonstrating the ranking of such numbers using comparative examples [143]. Furthermore, authors Wu and Mendel explore similarity and uncertainty measures attained in survey data [144]. These authors display an importance in survey design and linguistic information [144].

Other papers look into the ranking of various units with a focus on effectiveness and efficiency. Anderson and Peterson discuss the modification of a system used to evaluate the efficiency of decision making units [145]. The comparison method evaluates efficient Decision Making Units (DMUs) relative to a reference technology [145]. The authors discuss parametric methods and employ techniques using more information about the functioning of efficient units [145]. Kulkarni and Lingayat discuss the systematic analysis of product reviews and the ranking of product efficiency with the use of mining genuine reviews from customers [146]. The authors discuss opinion mining, specifically the extraction of information based on particular specifications and address the quality of the acquired feedback [146].

Other authors focus on the development of various frameworks to rank information in different systems. Kee and Karwowski focused on ranking perceived data, provided by subjects, involving joints, range of joint motion, and joint sizes [147]. The authors describe using numerical estimations to categorize verbal statements made by participants concerning joint motion stress [147]. Further work was done on ranking systems, specifically on ranking Turkish universities [148]. The authors developed a conceptual framework using various components that displayed strong relationships to the categorized and ranked units [148].

The ranking system review was continued on non-engineering racking systems, particularly those related to sports to broaden our view on types of ranking systems that may include components that may be applicable to this research.

The text "Who's #1?: The Science of Rating and Ranking", written by Amy Langville and Carl Meyer, discusses several ranking methods, the pros and cons of the detailed methods, and other implemented methods used in parallel [121]. Several of these ranking methods are detailed bellow.

Langville and Meyer present Colley's Method as a ranking system with modifications to winning percentages to allow for the incorporation of strength of schedule to rate the teams [121]. The authors present this as a bias free method that follows a conservation like property, however the method lacks in that it only takes into account the wins or loses of a team [121]. A similar method the authors discuss is Massey's Method, in which the analysis focuses on the performance of a team in terms of the final scores and games played [121]. This method is commonly used to predict the point outcome of a game [121]. Elo's Method, like that of Masseys Method, is used for predictions of wins or loses but is noted that it lacks in predicting past wins and losses, as it becomes more unpredictable when more ratings are used [121]. The method does reward a weaker team for defeating a stronger one and is good at estimating winning percentages [121]. The authors also discuss the Offence-Defense Method, in which offensive and defensive ratings are assigned to each team and used to determine an overall rating for the corresponding teams [121]. This methods is described as easily to implement, however does require some overall knowledge as one set of data will affect the others [121]. Keener's Method is similar to the Offence-Defense method in that one would be relating a rating of a given team to predict an overall strength of that team. Keener's method is depicted as flexible, customizable, and perhaps complex in that it may implement eigenvalues, complex numbers, and negative vales associated negative ratings [121].

This section outlined several topics in which ranking systems were applied in order to process information and make comparisons. Several authors applied ranking systems to fuzzy number systems, while others focused efficiency and effectiveness. Ranking systems designed for uses in ranking sports teams were also explored, and these documents depicted methods that may take into account wins vs. loses, team member statistics, and offensive vs. defensive information.

3.5 Research approach

This section describes two research questions and how these questions can be addressed using animal and environmental information. These questions deal with the research gaps, gaps three and four, that were previously presented and how a designer might conduct a more encompassing BID process.

3.5.1 Research Question 1: Can we produce animal or environmental similarity matrices to compare specification values of animals or environments?

Prior work introduced correlation matrices to attain a fitness score for an animal performing within a specific environment. Using that information that has been attained from the previous mentioned work, this work will explore similarity matrices to compare environments to one another in the hopes to investigate other animals that function within environments similar to that of the original environment.

Because this work revolves around the working environment, it would make sense to first compare environments to determine if a similar environments exists.

By comparing environments and attaining a similarity strength level, the environments considered for further use can be narrowed down to those with a very strong or strong similarity strength. This will allow for the investigation of animals that may be optimal for functioning within the original environment.

An environmental similarity comparison can be completed by comparing the specification matrix that describes one environment to another. This comparison can be displayed with the following equation, Equation 1:

$$A = S^T B S \tag{1}$$

Where matrices A and B are related via the correlation matrix S. Matlab has a built-in similarity/correlation coefficient solver built into the Parallel Computing Toolbox [149]. This built-in function implements the Pearson method for determining a correlation coefficient that represents the similarity between environments and is based on the simulated specification values. The correlation values were determined for the comparison of each environment and used to establish similarity strength ranges and corresponding qualitative classifications to describe the intensity of the strengths.

3.5.2 Research Question 2: Can we quantify animal mobility as a function and a set of numerical representations that can be ranked?

Animal mobility characteristics are calculated and quantifiable specifications used to determine how an animal moves within its environment. Because we are focusing on aero and hydro dynamics, the mobility characteristics focused on flying and swimming motions. These mobility characteristics are as follows:

- Flapping/Swimming
- Hover/Buoyancy
- Dive
- Glide
- Soar

The mobility characteristics for this research were determined from qualitative biological definitions used to describe the flight and swimming mechanisms for various animals. These definitions were then described with quantitative descriptions, using equations to explain the movement of the animals. These mobility characteristics are described below.

Flapping/Swimming

Flapping or swimming motion can be described with the thrust force that the flapping or swimming movement produces when an animal in question is moving straight forward. To attain the thrust force the mass and acceleration specification information, obtained through the animal background research, will be used. The thrust force equation can be described generally with the following equation [150]:

$$F_T = ma \tag{2}$$

Where *m* and *a* are the mass and capable acceleration of the animal, respectively.

Hover

The term hover can be used to descried the motion of an animal within a specific fluid with no movement in any direction. These terms describe the motion necessary for an animal to remain stationary using the appropriate forces. These forces can be described using the following equation [151]:

$$L = \frac{1}{2}\rho A C_L v^2 \tag{3}$$

Where the lift force L, is based on ρ, A, v, and C_L. These variables correspond to density, area, velocity, and coefficient of lift, respectively.

The term buoyancy will not be used to describe the motion of “hover within water” as the buoyancy of an object is based on the weight of the water displaced by the object in question. Therefore, the term and equation for hover will be used in both the air and water fluid situations.

Dive

A dive is movement that enables an animal to attain a high speed in a downward, almost completely vertical direction. The speed attained is terminal velocity and can be obtained using the animal specifications and described using the following equation [152]:

$$v = \sqrt{\frac{2w}{C_D\, \rho\, A}} \tag{4}$$

Where *V*, *w*, and *A* represent the velocity, weight, and frontal area of the object, respectively. CD and *p*, as before, represent coefficient of drag and density, correspondingly.

Within nature, dives are completed by animals condensing their figures, by either folding their wings or fins, allowing the animal to become more aerodynamic and/or hydrodynamic to complete the dive as fast as possible [153]. These calculations will be completed under the assumption that the wings or fins are completely folded against the animals' body and makes a negligible contribution to the animals' circumference.

Glide

The action of glide, or a gliding movement, can be described as the movement for an object to decrease in height, or increase in depth, as the object moves forward at a constant velocity [154]. A glide motion can be described mathematically using the equation to determine the angle at which an object glides, displayed below [155].

$$a = \tan^{-1}\frac{C_D}{C_L} \tag{5}$$

Where CD and CL represent the drag and lift coefficients, respectively, and *a* references the glide angle, negative to the horizontal flight path.

Soar

Soaring is a movement that requires thermal lifts produced by the working environments to allow for an animal to rapidly achieve height, based on a rate of climb, wing loading, and an achievable turning radius. The following equations will be used to describe a possible soaring motion [156], [157].

$$Wing\ Loading = m/S \tag{6}$$

$$\dot{h} = \frac{T - D}{W} V \tag{7}$$

Where, for wing loading, m is mass and S represents the wing area. Rate of climb, $\dot{h}$, is described by T, D, W, and V which correspond to thrust, drag, weight, and velocity, respectively.

Soaring, unlike gliding does not take into account for any flapping movement and are focused on the climb, or upward vertical motion that an animal may achieve [158].

The animal mobility characteristics within this research are being used as descriptors of animals and may be further described using free body diagrams, if so desired. The mobility characteristics previously described are used within the chosen ranking system, to help determine what animal will best suit the features needed to function within the working environment. It is important to understand that a couple of assumptions were made in order to complete the mobility calculation process as desired, and in particular when little to no information regarding animals could be found. The assumptions that were made are as follows:

1. CL was a specified value between all species
2. CD was determined based off of simulated and averaged skin friction and Oswald Efficiency values, and calculated aspect ratio values.

The CL was determined after conducting research on various coefficient of lifts for different types of birds as well as predicted lifts for other animal types. It was discovered that there was little to no information in regards to coefficient lift for animals. Due to the lack of information, it was determined that a coefficient of lift with the value of 1.5 was sufficient and effective with respect to low Reynolds numbers and this value would act as a placeholder until more data on the coefficient of lift for animals became available.

The coefficient of drag is determined by the coefficient lift, skin friction, the Oswald efficiency factor, and a related aspect ratio value. Skin friction, or CD0, was determined by simulation and the assumption to function with regards to a low Reynolds number, as with the coefficient of lift. The Oswald efficiency factor was determined based on assumption of a low Reynolds number, which could have potentially produced factors between 0.85 and 0.99. The efficiency factor was simulated and averaged, based on the simulations, similar to that of the skin friction. These values, like the other assumptions, are effective starting points and will serve as placeholders until enough documentation exists to replace them.

3.6 Ranking

The ranking process for this research is broken into three separate steps: calculation and statistical analysis, numerical values, and ranking values. These phases are described in detail below and how they were used within this research.

3.6.1 Calculation and Statistical Analysis

For the calculations, the mobility equations are calculated for each animal, using the animal specification described in [132] and a simulated 100,000 samples of these specifications. The samples were created using the “randn” function, built into Matlab, which produced the samples under the conditions of a normal distribution. The calculations produce the same number of estimated results for each mobility characteristic. These values were then used to conduct a basic Monte Carlo Simulation, which is a stochastic simulation [159], where histograms can be constructed and associated standard deviation and mean values can be determined for each mobility characteristic. A Monte Carlo Simulation was chosen to implement in this process due to its properties, which are listed below [160].

- Requires minimal assumptions
- Accuracy increases with the number of samples
- Uses simulated data created from observational data

This research will focus on a 95% confidence interval for the calculated values, between simulated minimum and maximum animal and environmental specifications.

3.6.2 Numerical Values

The mobility characteristic numerical values will be used twice within this process. First, the values of the mobility characteristics for each animal, will be ranked in terms of the desired performance goal for that particular characteristic. For flapping or swimming motion, the process will focus on which animal may produce the highest thrust force and therefore the animal with the largest calculated thrust force will be given the highest value. In regards to hovering, diving, and soaring within a fluid, the animal that produces the highest lift force, terminal velocity, and combination of rate of climb and wing loading, will be given the highest ranking in the respective sets. Glide, unlike the other mobility characteristics, will focus on a minimum value to determine the highest ranking, due to the relationship between the glide angle and the distance of the glide. A smaller angle will produce a longer glide and consequently a better gliding property.

3.6.3 Ranking Values

After determining the mobility and ranked mobility values, the ranked values of each animal are totaled and multiplied by the animal fitness score, which correlates how well an animal may function within a specific environment. The final score is then based on both animal mobility and a correlation between that animal and a chosen environment.

After the calculated values and corresponding animals have been ranked, and an animal chosen based on the ranking output, average values from the chosen animal's specifications are used to determine the possible average mobility characteristics that may be obtained in a bio-inspired vehicle to function within the chosen environment.

3.7 Animal Specification Mobility analysis (ASMA)

The proposed ASMA methodology that is set forth in this document, and using material from previous work in [132], describes how a designer may obtain an ideal biological inspiration for the use in designing an aero or hydro dynamic vehicle to function within a complex environment. The ASMA methodology id displayed in Figure 8 below:

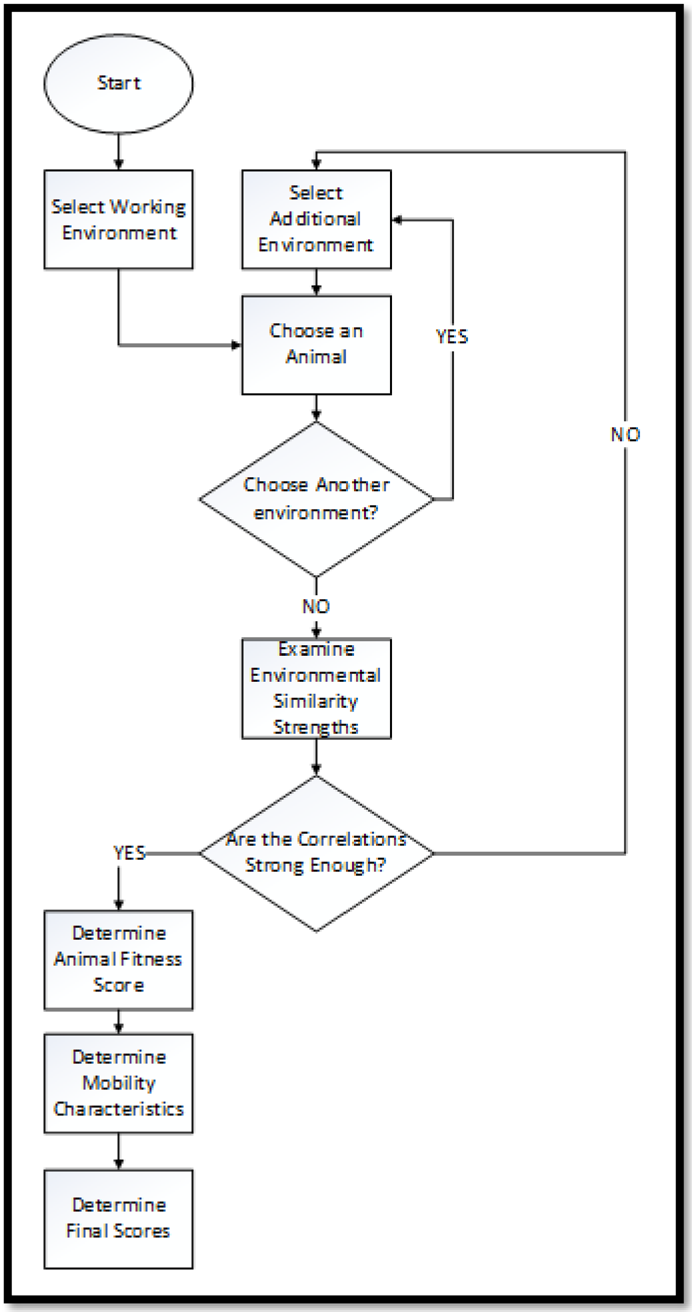


Figure 8: ASMA Flow Chart

The ASMA methodology involves a user selecting a working environment in which the vehicle will function and searching through other environments in order to compare a variety of animals to one another in respect to their individual functionality with the working environment. The user may also restart the process if the environments, in which the comparison animals inhabit, do not display a significant environmental similarity, based on user definition. If the similarity strength is considered strong enough, the user may move forward in the process, at which time the animal fitness scores, mobility characteristics, and final scores will be produced and outputted to the user

3.8 Results and Discussion

This paper builds on previous work that defined environmental and animal specifications to support designers in matching desired product requirements and operating environment with animal inspiration coupled with typical environmental conditions [132]. That work presented an example of a harp seal as the animal inspiration. In summary, that work showed that the harp seal may be outperformed by a stingray or an orca. This result was in terms of the correlation strength between each animal's specifications and the specifications of a polar ocean environment, specifically the Northern Atlantic Ocean. This paper continues that example to showcase both similarity matrices and ranking systems to compare environments and rank various animals based on defined mobility characteristics, respectively.

This section will discuss the continued example of the harp seal and how this animal, as well as comparable animals, may function within an environment and what may be achieved in terms of each animal's mobility characteristics.

3.8.1 Environment similarity

Environment similarity, based on measurable specification, can help designers broaden their area of possible inspiration. While designers will be given a working environment to design for, they may find other inspirations by looking towards related environments and the animals within them.

For this example, the working environment for a harp seal is a polar ocean. This environment includes elements of open ocean, polar, and mountain environments [132]. The polar ocean environment was compared to other environments, using a similarity matrix similar to that of the correlation matrix described to attain the fitness score. The function used, "corr2" results in a single representative number that denotes the likeness of one environment to another. The similarity test resulted in the corresponding similarity strength:

Table 18: Environment Similarity Correlation Strength

Environments	Correlation Strength (%)
Canyon	19.4
Polar	100
Reef	24.8
Taiga	27.7
Kelp Forest	23.5

It can be seen that these correlation values are relatively low, under 30 percent, apart from the polar environment which served as the datum. While these values are representative of the obtainable information used to for this project, there could be a couple factors that play towards some inaccuracy within the correlation strength. First, there were assumptions made about locational information and respective simulated specification data. It is important to remember that the simulated values were based on cited and visually examined information and imagery, respectively. This information should be continually refined and should be updated as more biological information becomes available. This is likely to impact the strength of the correlation values. Second, there were assumptions made during the process of obtaining the environmental specification values. In particular, the size of obstacles and obstacle density values were estimated with the understanding that any obstacle more than 20ft away would be avoidable by larger animals, simplifying obstacle cluster density, and the obstacles within images were evaluated based on color assessment. This means that the density of a given area is evaluated based on a comparison of the smallest obstacle, or cluster of obstacles, to the largest obstacle, or obstacle cluster. The obstacle information has a somewhat large impact on the correlation strengths, as three of the eight environmental specifications involve obstacle information, which will possibly impact the environmental similarity correlation strength. To this effect, the obstacle information should be continually refined to obtain more accurate correlation strengths.

3.8.2 Ranking evaluation

This section discusses the statistical and numerical mobility analysis of the chosen animals against a specific working environment. This discussion will again continue the harp seal example, discussed earlier, and will incorporate the other environments explored within this research example.

Statistical Analysis

The statistical method performed in this analysis process is a Monte Carlo simulation. The simulated values were created randomly, between documented specification information used as boundary conditions for the minimum and maximum achievable conditions. The Monte Carlo evaluation used in this research is based on the assumption of a normal data distribution and is created as such [159], [161], [162]. This assumption can be met as animal specifications tend to follow a normal distribution [163]. The analysis presented in this work applied 100,000 samples for each specification value. These values were used to determine the same number of achievable mobility characteristics within a 95 percent confidence interval. The histograms and the overlaying curve, corresponding to the produced confidence interval, standard deviations, and variances, are presented in Annex A. The following are the numbered mobility characteristics in the order they appear in Annex A.

1. Lift Force
2. Glide Angle
3. Terminal Velocity
4. Wing Loading
5. Rate of Climb
6. Thrust Force

Numerical Values and Ranking System

After the conclusion of the statistical analysis, the average values of each calculated mobility characteristic for each animal were used to determine the ranking of each animal. Each mobility characteristic was ranked from highest to lowest, highest representing a more desirable result. This allows for a designer to focus on better results which could mean either larger or smaller values depending on the needs of the designer. These ranking values are then totaled for each animal.

The final step in determining a better animal inspiration involves the reimplementation of the animal fitness scores, described and detailed in [132]. The animal fitness score portrays how an animal functions within a particular environment. Each animal that is chosen and ranked through the use of the algorithm is done so using the chosen working environment. Therefor each fitness score is representative of the corresponding animal within the initially chosen environment and not the environments that the animals inhabit. The fitness scores for each animal were multiplied by the totals of the ranked mobility scores. A flow chart of the ranking system is detailed below in Figure 9:

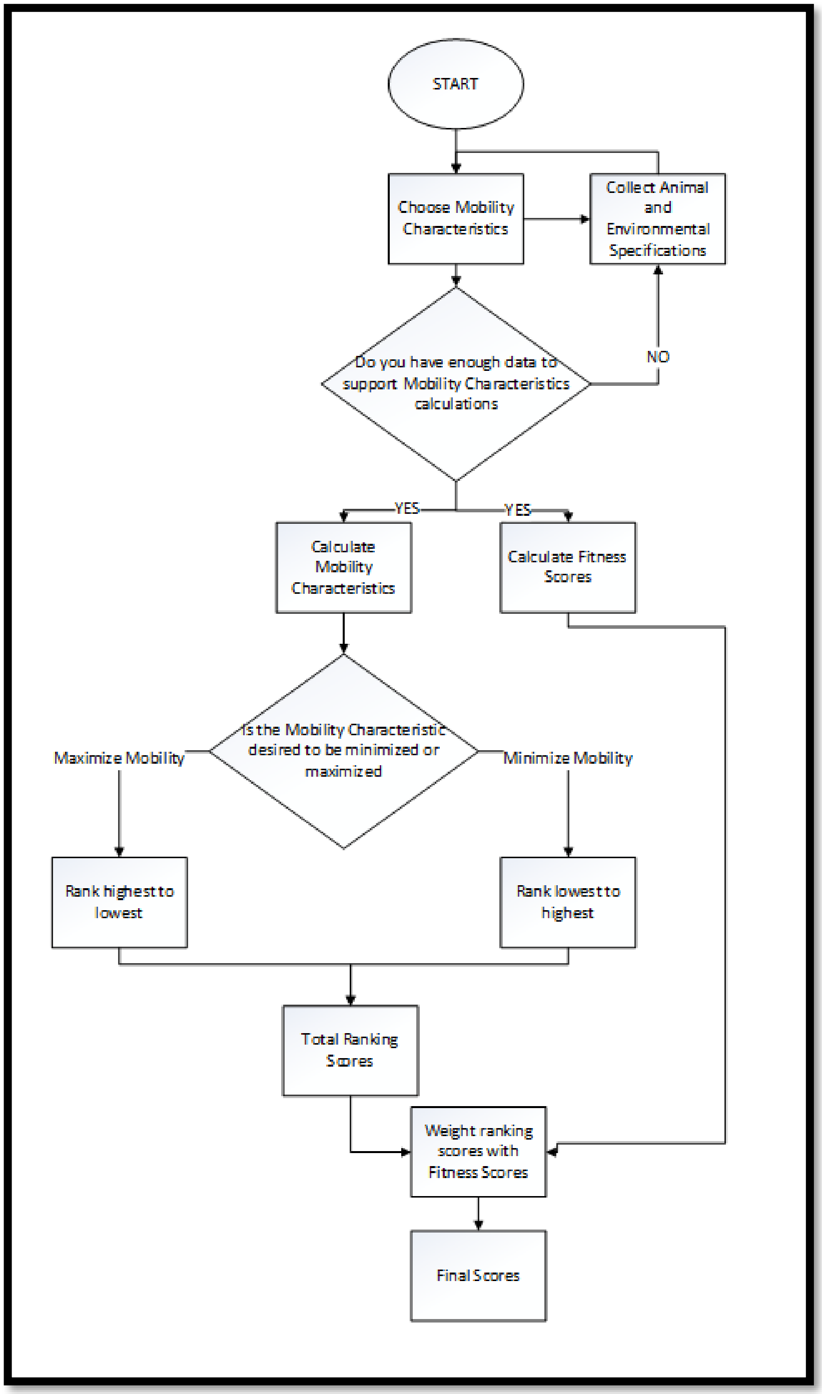


Figure 9: ASMA ranking system

Continuing the harp seal example, the following are final scores for each animal used within this example.

Table 19: Animal Final Scores

Animal	Final Score
Owl	0.099
Eagle	0.379
Orca	98.065
Penguin	0.329
Frigate	2.398
Harp Seal	35.918
Stingray	95.092

For this process, the scores were normalized between zero and one to make the scores more easily understood. The data presented above, in Table 19, shows that the Orca, and stingray animals scored higher than the original animal, a harp seal, for the polar ocean working environment.

3.9 Conclusion

In this paper, four research gaps have been addressed and a proposed method of design for biological inspirations has been described and used in an example. The research gaps focused on in this paper are lacks in the BID process involving design automation, defining what makes a design "better", mechanical ranking systems based on biology, and a focus on animal mobility. The example is continued from previous work done, seen in [132], and adds components involving the calculation and ranking of various mobility characteristics. Through the documented example, it has been shown that animals from numerous environments may be compared in regards to their mobility characteristics. Within the example, seven animals were ranked against one another with respect to a polar ocean environment, which resulted in the orca and the stingray outperforming the original animal, a harp seal. The animal's mobility characteristics were also examined through a Monte Carlo statistical analysis, which produced calculated mobility characteristic histograms and an associated 95 percent confidence interval.

3.10 Future Work

Future work for this project should focus on validating the method and work done in both this paper and the prerequisite paper about the process of determining a proper bio-inspiration for a specified working environment. Validating techniques may include a comparison of studies involving specific mission requirements. Validation may also include both bio-inspired and bio-mimicry techniques, as both of these could compare possible achievable mobility characteristics and respective animal choices.

Annex

Owl Mobility Characteristics

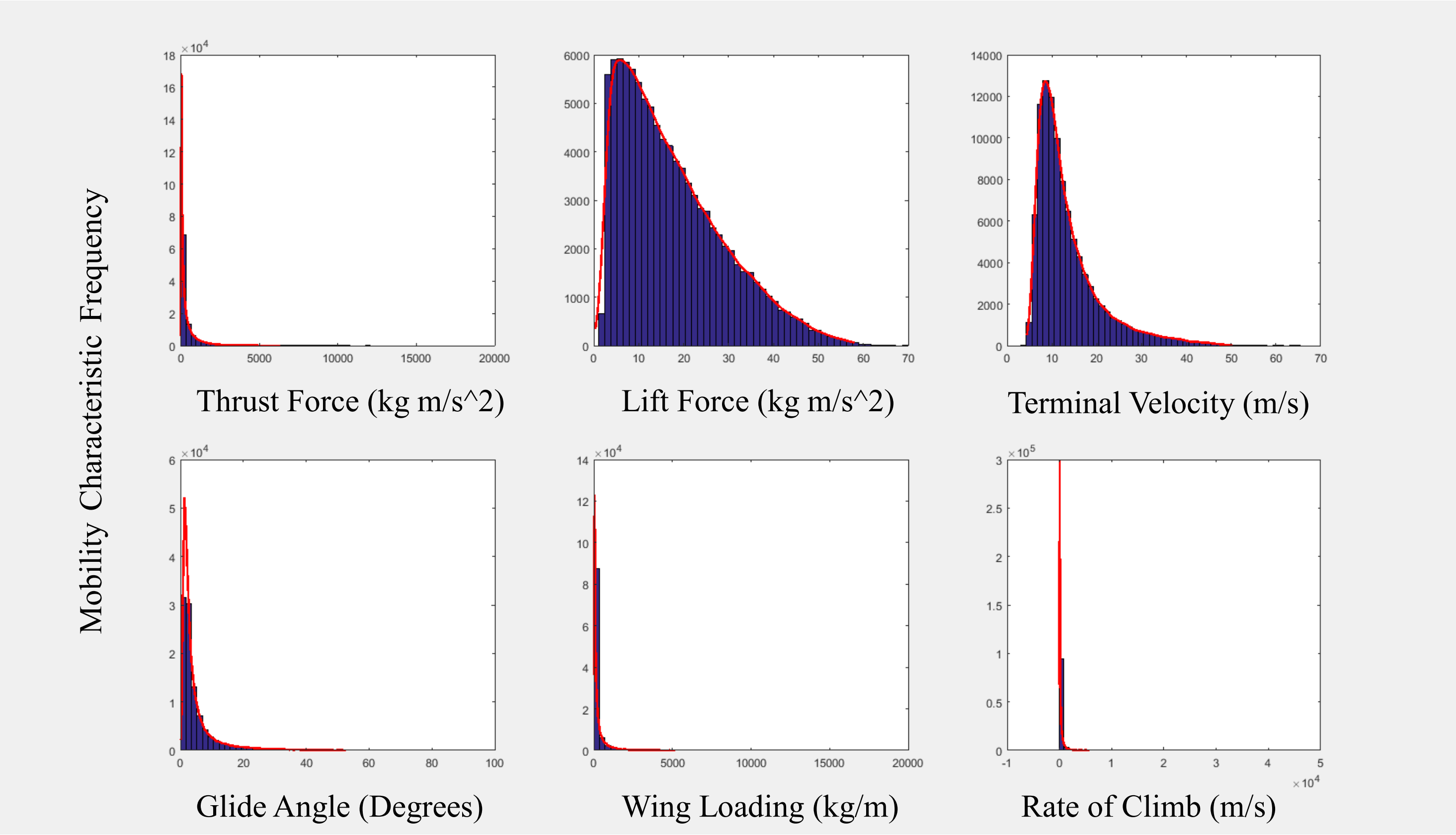


Figure 10: Owl Mobility Characteristics

Annex (Continued)
Eagle Mobility Characteristics

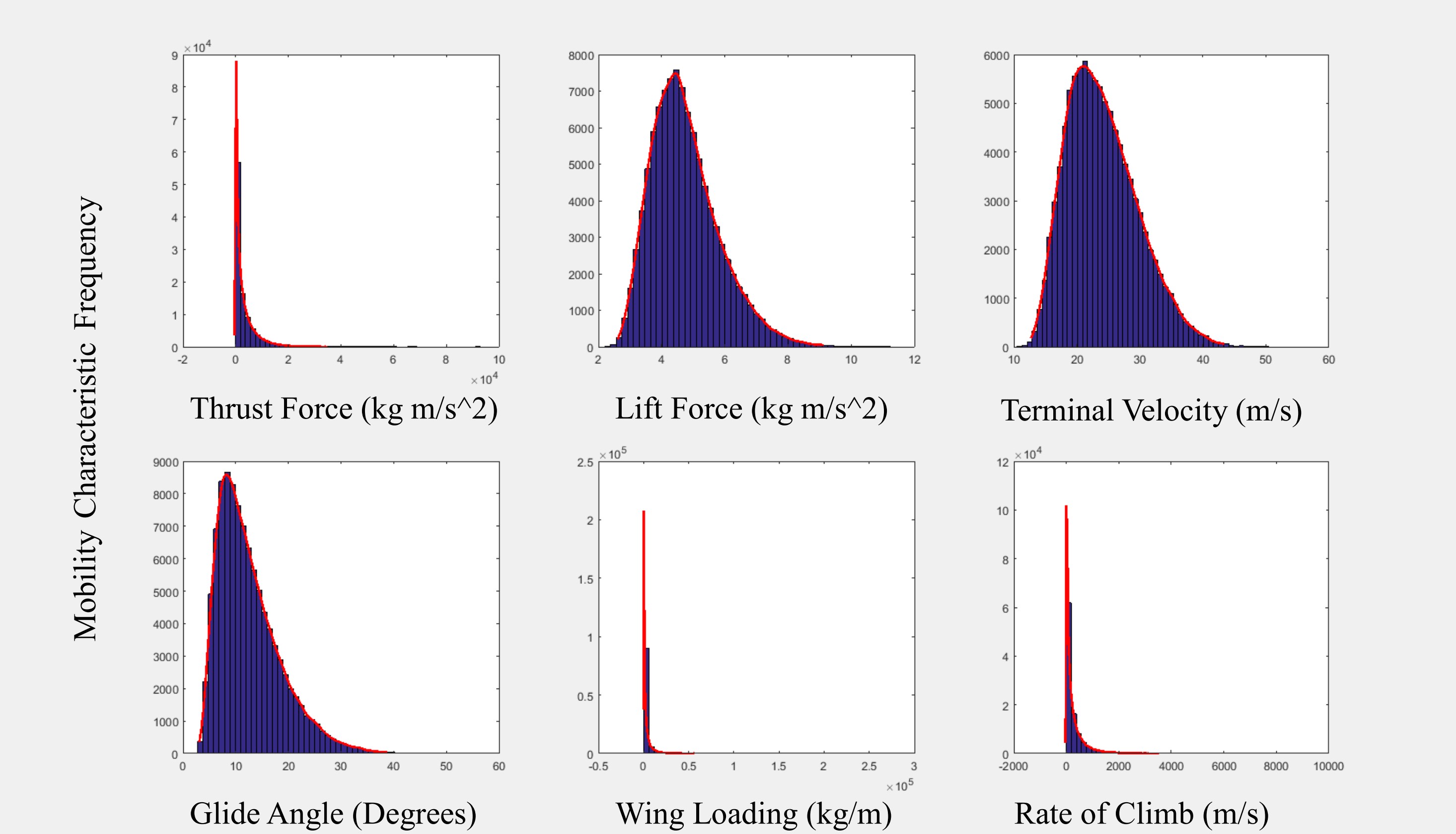


Figure 11: Eagle Mobility Characteristic

Annex (Continued)

Orca Mobility Characteristics

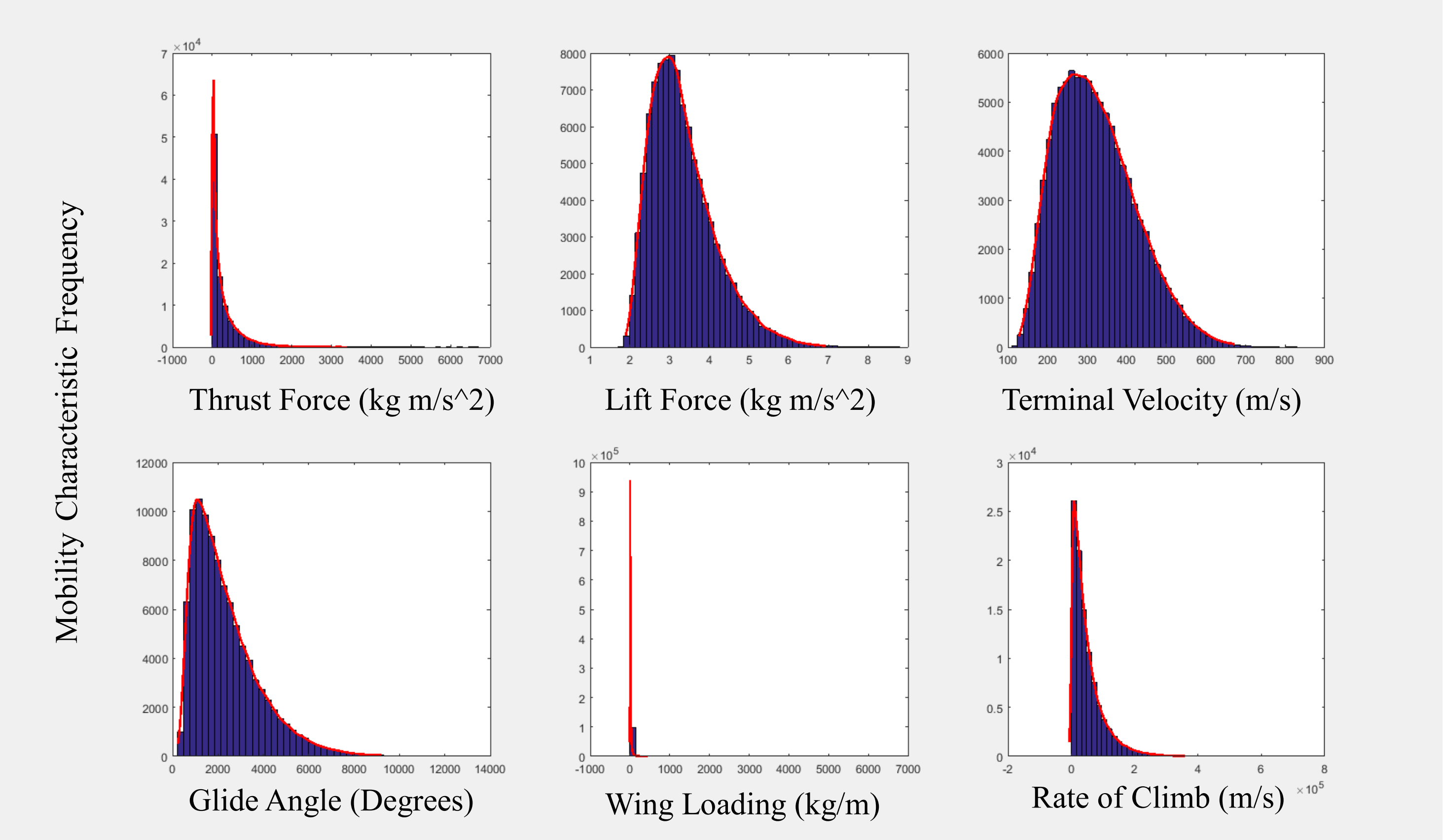


Figure 12: Orca Mobility Characteristics

Annex (continued)

Penguin Mobility Characteristics

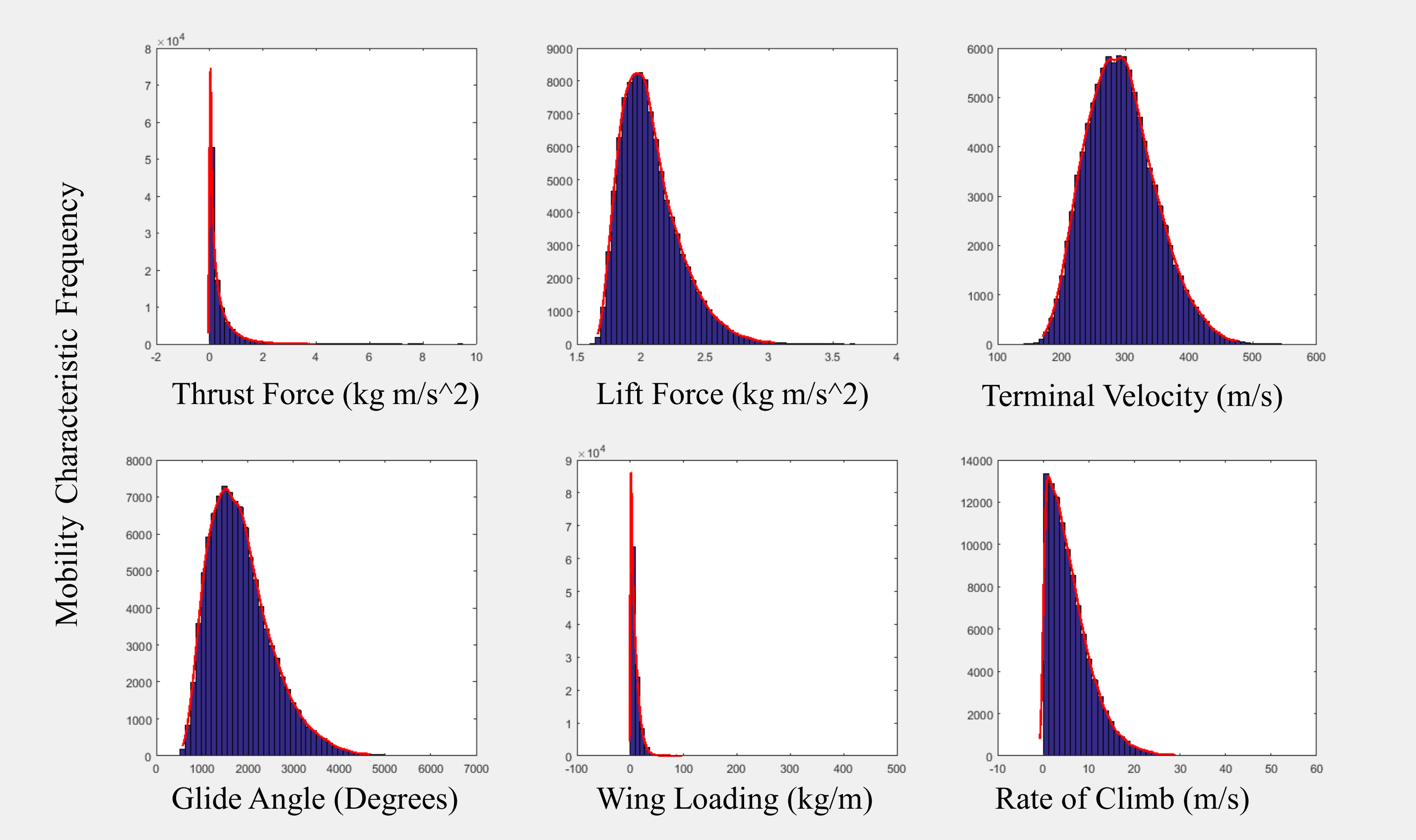


Figure 13: Penguin Mobility Characteristics

Annex (Continued)
Frigate Mobility Characteristics

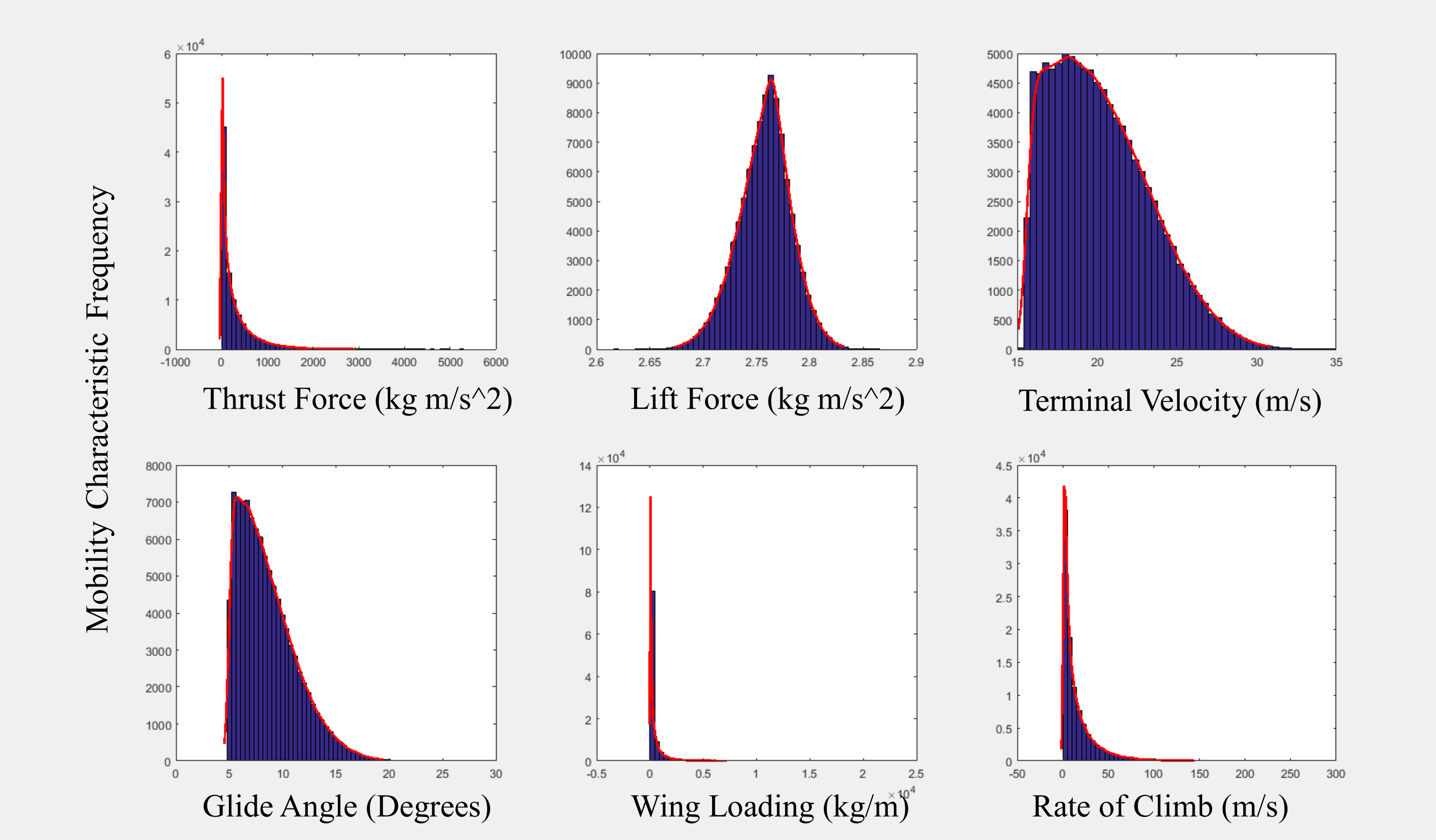


Figure 14: Frigate Bird Mobility Characteristics

Annex (Continued)
Seal Mobility Characteristics

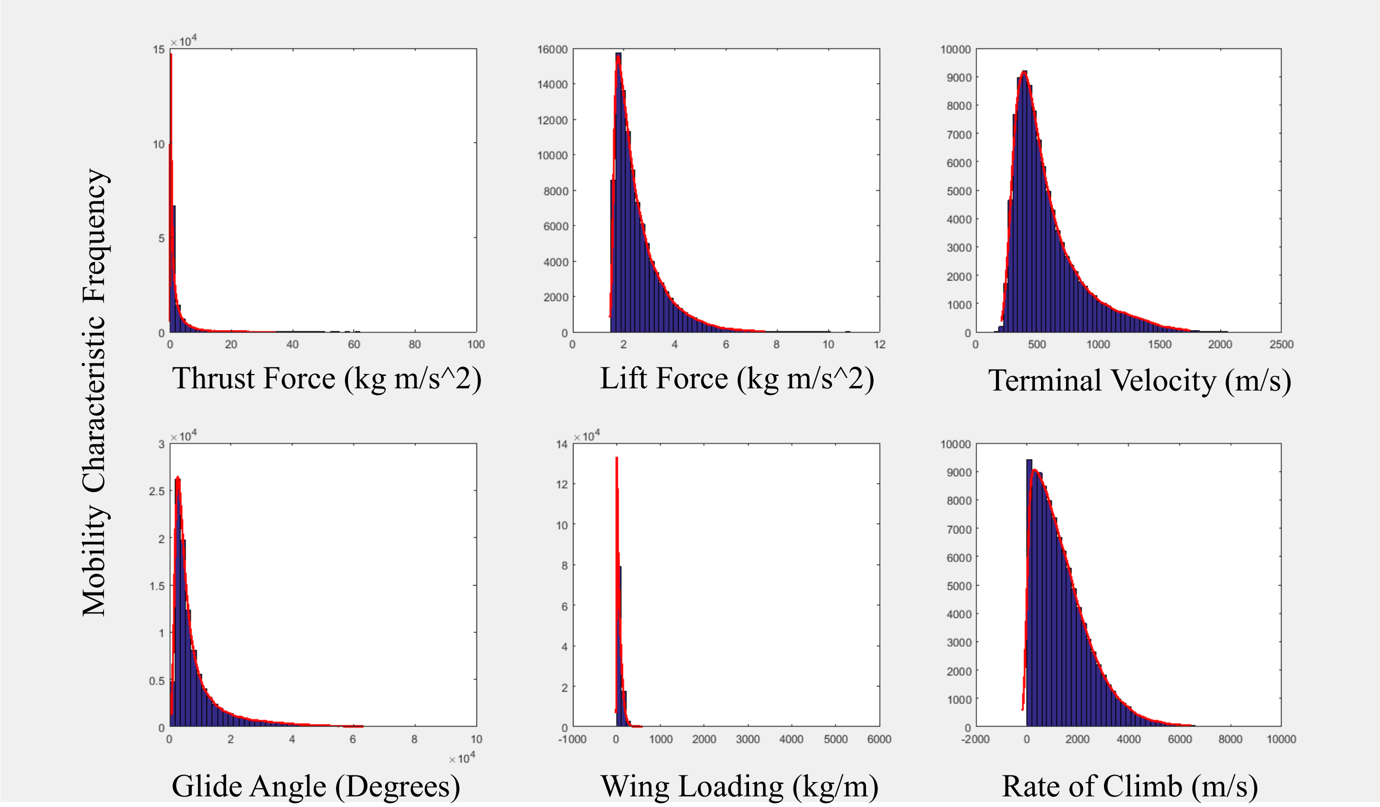


Figure 15: Harp Seal Mobility Characteristics

Annex (Continued)
Seal Mobility Characteristics

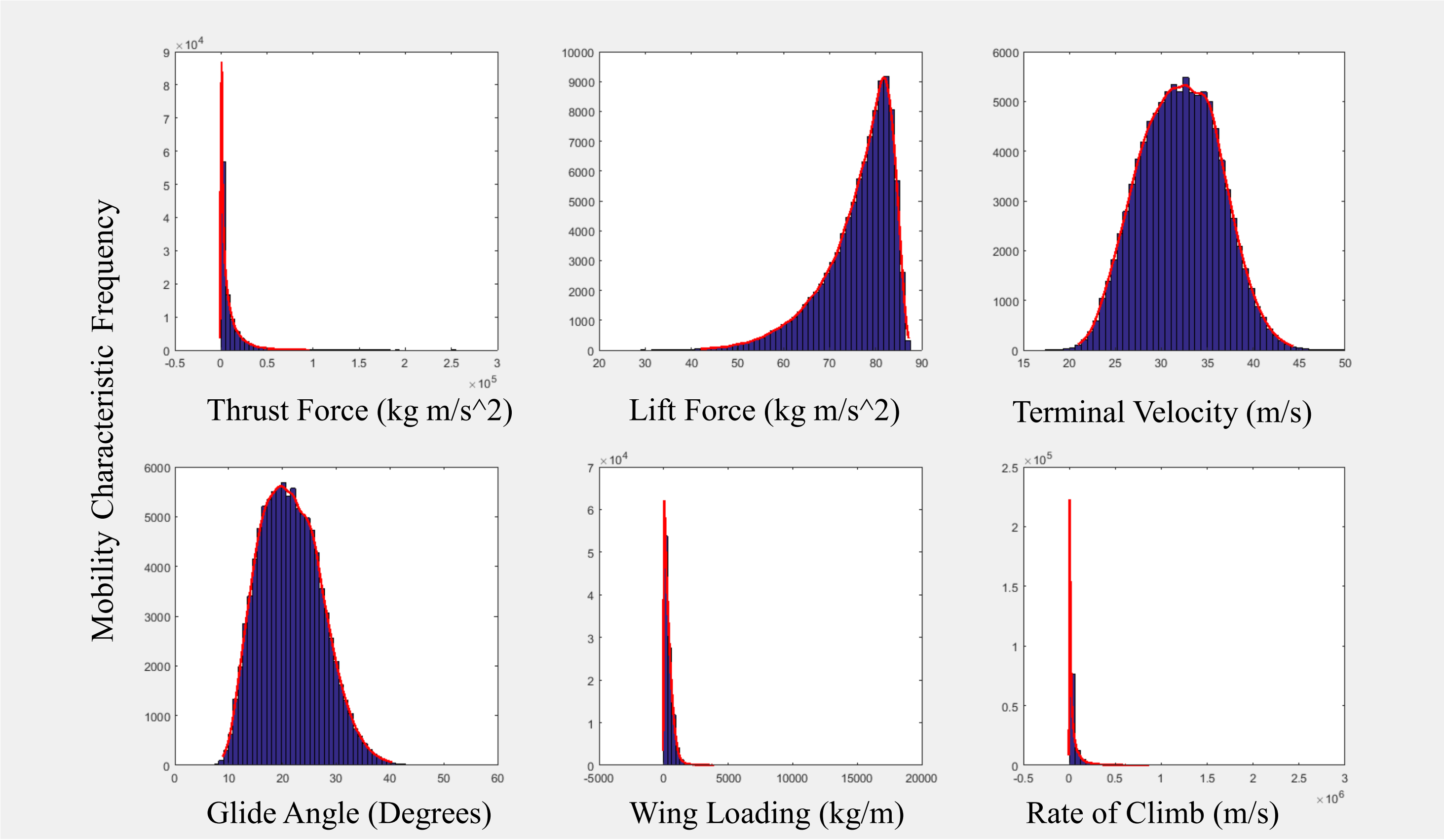


Figure 16: Stingray Mobility Characteristics

Proceedings of the ASME 2019 International Design Engineering Technical Conferences
& Computers and Information in Engineering Conferences
IDETC/CIE 2019
Date TBD, 2019, City, State
DRAFT DETC

VALIDATION OF ANIMAL SPECIFICATION AND MOBILITY ANALYSIS USED FOR BIO-INSPIRED VEHICLE DESIGN

Danielle M. Jackson, Marshall R. Miller, Brian A. Johnstone, and Robert B. Stone
Design Engineering Lab
Oregon State University
Corvallis, OR, USA

4. Manuscript 3

4.1 Abstract

This paper addresses research gaps in bio-inspired design (BID) theory through a validation study of novel methodology to direct designers to appropriate biological phenomena to use as inspiration in the design of aerodynamic and hydrodynamic vehicle design for use in complex environments. The proposed design methodology, designated as the Animal Specification Mobility Analysis (ASMA), is validated through three case studies that span the scope of BID application. ASMA involves automation within the design process and creates standards for determining a useful bio inspiration based on quantifiable and ranked mobility descriptors. The validation process described in this document addresses bio-inspired design methods, both mechanical to biological and vice versa, as well as the biomimicry design process. Results from the bio-to-mechanical, and biomimicry design validation tests concluded that the proposed methodology showed promise in that similar scoring between the biological organisms and the respective mechanical counterparts were achieved. The mechanical-to-bio validation involved using a fictional scenario based on factual information and unlike the other tests, used different mobility characteristics. This established the ability to restructure the mobility analysis to fit the parameters of a given mission.

4.2 Introduction

This paper aims to validate previous work done on a bio-inspired design process which was proposed to help guide designers towards potential bio-inspirations for the design of aerodynamic and/or hydrodynamic vehicles [132], [164]. The previous work done for this research focused on three main tasks: describing animals and environments using measurable characteristics, describing the functionality of an animal within a specific environment in a quantifiable manner, and ranking potential bio-inspirations based on performance capabilities [132], [164].

The goal of this paper is to validate the Animal Specification Mobility Analysis (ASMA) methodology, which is detailed in the previous work, by presenting scenarios that may test the capability of the ASMA methodology for the use in designing vehicles to function within a specified environment.

4.3 Motivation

The motivation for this research is driven by the need to address research gaps found within the current literature of bio-inspired design and respective methodologies used in the design processes. This research has developed and implemented a bio-inspired design methodology that focuses on for main research gaps that were observed in literature. These gaps are listed below:

“BID gap 1: *A lack of automation in the bio-inspired design process.* A need exists for a methodology that supports automation in identifying proper bio-inspiration phenomena to solve a problem in order to streamline the design process and create a focused search strategy for the designer” [132].

“BID gap 2: *A missing standard for determining a “better” inspirational source from biology.* There is a need for a methodology that allows a user to design based on measureable biological characteristics to attain desired functionality factors” [132].

"BID gap 3: *There is no mechanical ranking system based on biology and the natural world.* The need exists to link the biological and mechanical worlds through measurable, organize-able, and sortable characteristics [164].

BID gap 4: *A lack of focus on capability and mobility linking the bio and mechanical world exists.* Designers need a methodology that focuses on the biological characteristics of both the bio-inspiration and the mechanical design" [164].

The purpose of this paper is to validate the methodology proposed in this research. Specifically, this paper will address the validation by comparing the functionality of various designs with designs found in nature. The functionality of the compared designs will be based on an achievable mobility within a complex environment. The validation methods presented will take into account the various bio-inspired design methods, and by doing so will incorporate different comparison techniques.

4.3 Background

The work presented in this document will focus on the validation of a methodology, developed to help designers within the field of bio-inspire design. The information presented in this section will outline work done in the field of bio-inspire design, current tools used in bio-inspired design, and several validation strategies research to refine the strategies presented within this document.

4.3.1 Bio Inspired Design

This section will be comprised of a literature review that will describe various works completed within the field of bio-inspired design.

Activity in the field of bio-inspired design has drastically increased over the last decade, particularly within the field of aerodynamics. Research has focused on work done towards micro air vehicles, the 3-D manipulation of wings, and the geometrics involved in deployable wing elements [69]–[71]. Other authors focused more on morphing wing studies, in which the reviewed papers discussed performance increases to aircraft and wind turbines due to composite manufacturing techniques, material choices, and adaptability of a wing [75]–[77].

Robotics is another sub-field that has flourished within the field of bio-inspired design. Work has been done on determining a mechanical advantage on bio-inspired joints as well as robotic hand implantation, and bio-inspired tendon driven actuation within an arm [80]–[82]. The research of robotics continued to show importance through the work done on locomotion. Reviewed papers included various projects on micro-robotics, some specifically addressing underwater locomotion, and another paper discussing the optimized pattern movement in regards to the gait of locomotion [83]–[86].

Research has been done in the field of biomimetics, and in a specific paper the authors presented a model for problem driven design processes that may be used for problem solving activities [165]. These authors mapped a set of tools used in the biomimetic process and evaluated these tools using assessment sheets designed to assess the tools on both theoretical and practical applications[165].

4.3.2 Tools for Bio Inspired design

Tools used in bio-inspired design vary greatly in application and provided resources. The tools discussed in this section are web based applications that provide information on and about nature, design, and data collection. Each of these tools have been implemented into schools as learning aids and are still continuing to grow.

Ask Nature

Ask Nature, provided by Biomimicry Institute, is an online catalog that help designers by providing nature driven solutions to innovators, and is focused towards worldwide challenges[166], [167]. Ask Nature's online library features over 1800 informational sources that discuss natural phenomena and can be applied to hundreds of bio-inspired applications [166]. The Ask Nature database is arranged to allow users to ask questions in regards to how a biological source may solve a problem. The Ask Nature tool also includes various resources such as literature, media, instructional material, and professional development tools [166]. This compilation of various works bring together biological strategies and inspirational ideas to answer questions in regards to how we, as innovators, may achieve goals or what we can learn from biology and how to implement it into our lives [166].

Design Repository

The Oregon State University Design Repository is an ongoing research project, used to support design research activities by means of archiving design knowledge [168]. The repository categorizes information based on systems, artifacts, functions, and flows. The repository aims to presents information with associated function and flow diagrams, as well as definitions to help designers understand the functionality of systems and artifacts, or components, of a system [168]. The design repository is not specifically for bio-inspired design, but has been developed for a wide range of uses within the design community [168].

Washington Nature Map

The Washington Nature Mapping Program is an online tool, developed with the idea to allow people from all backgrounds to participate in data collection with regards to various plant and animal life around the county [169]. The Nature mapping tools include maps, animal and plat fact sheets, and data sheets reporting on the location of different animal species and habitat classification [169]. The program also implements other tools, such as GIS or ARCGIS, to develop maps and connections between data sets and special scales [170]. The Nature Mapping program includes published works, links to other websites of interest, and information for educators [169].

4.3.3 Validation Strategies

The validation of engineering design processes has been previously considered “formal, rigorous and quantitative.” However, these views have recently been refuted and an alternate perspective has been presented in [171], [172]. This new view describes validation to be of a “relative, holistic and social assessment”, which focuses on the need for theoretical and empirical validation of both structure and performance [171], [172].

In other research it has been proposed that validation methods from medical fields may be applicable to confirm the effectiveness of engineering methodologies [173].

This work discusses the usefulness of seeking validation techniques from the medical field as engineering method strive for effectiveness in several aspects of success including quality, performance, cost, and time [173]. The author presents an analogy between medical research and design theory with specific links to what aspect is being validated. These links include any affected entities, outcomes, involved developers and professionals, and standards [173].

There are various validation strategies that are related to bio-inspire work. The strategies discussed in this section involve validation methodology and validation methods applied to bio-inspired deign processes involving optimization algorithms.

Authors Versos and Coelho developed a validation methodology for bio-inspired designs developed through an iterative process [174]. The process implements the use of surveys, conceptual-analytical arguments, and standard engineering design techniques [174]. The authors address five goals and validation procedures to evaluate the accomplishment of a goal [174]. The goals were then related to one or more requirements that describe the needs for a goal to be satisfied [174]. The survey for the project included a qualitative ranking system, which described the best to worst ranking that a product may have based on user preference and personality profile and the message the designer was trying to relate through the product [174].

4.4 Prior Work

Prior work on the topic by the authors has focused on formulating the underpinnings of a BID methodology that enables designers to find appropriate biological phenomena for inspiration given the environment in which a desired product will operate [132], [164]. The focus of this paper turns to validating that work. Significant discoveries include the correlation of environmental and animal specifications, development of fitness scores that represent the functionality of an animal within an environment, comparison of environments based on similarity measures, and quantification of animal mobility [132], [164]. Thus far, the project has focused on developing a method to help designers design an aerodynamic/hydrodynamic vehicle to function within complex environments [132]. The prior work has culminated in a method to design aerodynamic/hydrodynamic vehicles to function within complex environments. These environments were established on the basic environment components. Both the complex environments and the animals explored are described using specification values, which were then used for developing an animal fitness score and calculating mobility characteristics, used to describe the movement ability of an animal [132]. The developed methodology then implemented a ranking system based on the strength of the mobility characteristics and the respective fitness score [164].

4.5 Validation Approaches

For this research, there will be three validation techniques used to help determine the validity of the results produced by the combination of the animal fitness scores and the mobility ranking system. These validation approaches are mechanical-to-bio, bio-to-mechanical, and biomimicry. We can compare the validation methods presented in this work to the validation aspects presented in [171]. The following table, Table XX, represents which validation aspects are focused on, and describes the details of implementation.

Table 20: Validation Square Aspect vs. Proposed Validation Methods

Validation Type	Theoretical Structure	Empirical Performance	Theoretical Performance
Validation Aspects	Correctness of Method	Performance of Solution with Respect to Problem	Performance of solution Beyond Respect to Example
Method	Biomimicry	Mechanical-to-Bio	Bio-to-Mechanical

The proposed validation techniques address all but one validation aspect: empirical structure validation. This validation aspect focuses on the appropriateness of an example problem used to verify a method. This aspect is not directly addressed in this work; however, considerations were made in respect to the selectiveness of the examples used in the presented validation scenarios. The presented validation approaches are detailed below.

4.5.1 Bio-to-Mechanical Validation

For a mechanical-to-bio validation, this research will compare the required and measurable performance properties of an aerodynamic or hydrodynamic vehicle, and its corresponding mobility characteristics, with the achievable animal specifications and respective mobility features that may be obtained by implementing the proposed design process and selecting a biological inspiration based on inspected animals.

Specifically, the mechanical-to-bio validation process is comprised of comparing the simulated Orca data with the information about the Seabreacher Y, provided by Innespace Productions [175]. The Seabreacher Y was designed with a killer whale body style, and was updated from the Seabreacher X vessel with new design features such as a larger whale tail, pectoral fins, and a functioning blowhole [175].

The Seabreacher Y is similar in size and shape to that of an actual orca [175], and should prove worthwhile to evaluate in terms of the predicted mobility characteristics in comparison to that of an Orca whale. The information given on the Seabreacher Y will be used in comparison with that of the animal mobility simulated samples provided in this research. This comparison will depict whether or not the proposed method can evaluate an animal and may produce a bio-inspired design with respective achievable mobility characteristics.

4.5.2 Mechanical-to-Bio-Validation

A mechanical-to-bio validation process involves selecting an appropriate animal that best meets corresponding specifications and mobility characteristics within the environmental constraint of a mission using the environment to animal correlation procedure. The mechanical-to-bio validation process is similar to that of the bio-to-mechanical validation in the sense that a designer may evaluate number of possible bio-inspirations to help guide a designer. However, the mechanical-to-bio validation process implements the “bridge to technology” process, displayed in Annex A. This process allows a designer to identify a biological inspiration and use it to create a solution that meets the needs of a designer, for a particular mission. This is unlike the bio-to-mechanical validation process, which focusses on developing a solution to a mechanical problem that may yet to be fully defined.

The mechanical-to-bio validation process will explore a known mechanical problem, described as a mission, and will evaluate various biological organisms in terms of effectiveness in accomplishing customer requirements, which are set forth by the mission statement.

4.5.3 Biomimicry Validation

The biomimicry validation example will incorporate the measurable characteristics from a type of robotics project, in which the robot specifications will be used to produce the corresponding mobility characteristics that the robot may achieve. These mobility characteristics will be compared with those of the natural version of the robot, being the animal itself, as well as other animals and the mobility characteristic that may be produced by each animal.

The biomimicry validation process involves comparing the simulated specifications of a stingray and the specifications of a robotic stingray, the Aqua Ray, provided by the company Festo [176]. The Aqua Ray is a remote controlled water-hydraulic manta ray, equipped with a flapping-wing propulsion system. Festo claims that “rays are perfectionists in submarine flight and glide” and Festo has recreated this flight movement with the use of bionic fluidic muscles[176].

Based on the information given, this paper will evaluate both the simulated and robotic rays in terms of the mobility characteristics. The Monte Carlo analysis will be performed on the simulated results, while the specifications from the Aqua Ray robot will be used to calculate one set of mobility characteristics. The Aqua Ray mobility characteristics will be compared to the Monte Carlo results to determine if the robotic results fall within the predicted 95 percent certainty range for the animal mobility analysis.

4.6 Results

This section discusses the results of the validation tests performed for this research. Each validation subsection will contain discussion on the specifications of the bio-inspired designs being used as comparisons, the fitness scores, and the mobility characteristics.

4.6.1 Bio-to-Mechanical Validation Results

The bio-to-mechanical validation compared the Seabreacher watercraft to that of its biological counterpart, an orca whale, as well as several other animals and their respective specifications. Each potential animal, or watercraft, was compared and ranked with the open deep ocean working environment, meaning each fitness score produced was respective of the chosen working environment. A watercraft, such as the Seabreacher, may be subjected to the fitness scoring computations to allow for a designer to evaluate the craft in terms of the mobility characteristics. This example also displays the capability of the ASMA process to handle mechanisms as well as their biological counterparts. The fitness scores for each animal are listed below in Table 20:

Table 21: Bio-to-Mechanical Validation Fitness Scores

Animal Designation	Animal	Fitness Score	Rank
A1	Owl	664.30	8
A2	Eagle	2495.39	6
A3	Orca	597778.22	2
A4	Penguin	2180.94	7
A5	Frigate	15644.97	5
A6	Seal	233539.60	4
A7	Stingray	590050.19	3
A8	Seabreacher	3640777.60	1

From Table 20, it can be seen that the orca, the stingray, and the Seabreacher scored significantly higher than any of the other animals, leaving a 40% gap between the animals that ranked 3rd and 4th. Table 20 also includes the ranking of each animal, from 1st place to 8th, based on these scores.

As designers, we can interpret these results to mean that these animals and this watercraft may be capable of functioning within the deep open ocean environment similarly, and may function at a higher degree than the other animals used in this test.

Following the fitness score calculations, each animal was ranked on potentially achievable mobility characteristics, as described in [132]. The following table, Table 21, displays the mobility characteristic ranking system for this validation test.

Table 22: Bio-to-Mechanical Validation Ranking Scores

	A1	A2	A3	A4	A5	A6	A7	A8
Lift	7	2	8	5	3	1	6	4
Glide Angle	4	6	5	3	2	1	8	7
Terminal Velocity	6	3	4	8	7	2	5	1
Wing Loading	6	3	4	8	7	2	5	1
Rate of Climb	2	5	7	1	8	6	3	4
Thrust	7	8	2	1	3	5	6	4
Totals	32	27	30	26	30	17	33	21

The calculated mobility characteristics were ranked from 1 to n, n being the total number of animals considered. The ranking values are shown in Table 21, above. The mobility characteristics were ranked highest to lowest, highest being a better number, except of the glide angle. The glide angle was ranked lowest to highest, as a smaller glide angle is ideal in that it will produce a longer glide. Throughout the ranking system, a higher-ranking value is more desired.

These ranking values represent the average mobility characteristics that may be obtained with 95 percent confidence. The confidence intervals for each mobility characteristic are displayed in Annex B. These intervals were created using a Monte Carlo simulation, in which the uncertain variables were the simulated specification values. These values are considered uncertain as the true measurement for the 100,000 samples are unknown and therefore simulated.

After the ranking values are totaled, those values are multiplied by the fitness scores, respective to each animal. Mathematically, this is weighting the ranking values, based on the fitness scores. The weighting is important as it represents the compatibility of the animals within the chosen environment. These values are then normalized between 0 and 100 for ease of interpretation. These final score values are listed below in Table 22:

Table 23: Bio-to-Mechanical Validation Final Scores

Animal	Final Scores	Normalized Scores	Rank
Owl	21257.6	0.000278	8
Eagle	67375.53	0.000881	6
Orca	17933347	0.234557	3
Penguin	56704.44	0.000742	7
Frigate	469349.1	0.006139	5
Seal	3970173	0.051927	4
Stingray	19471656	0.254677	2
Seabreacher	76456330	1	1

The final scores indicate to the designers what animals should provide useful bio-inspiration for their product or system design task. The final results, listed above, point towards an orca, a stingray, and the Seabreacher as viable bio-inspiration. In terms of the validation of the proposed method, the Seabreacher scored close to that of the orca, with respect to the other animal scores. Though the orca did score higher than the Seabreacher in regards to the mobility characteristics, the Seabreacher fitness score was over 12 percent larger than that of the orca. This resulted in the Seabreacher achieving a higher final score. This validation test displays similarity between mechanical designs and their corresponding bio-inspirations, verifying the methodology and demonstrating its usefulness.

4.6.2 Mechanical-to-Bio-Validation Results

The mechanical-to-bio validation method involves using the methodology to determine a viable bio-inspiration based on a mission profile. The mission outlined within this example will focus on needed attributes and a stated location in which the mission will take place. The needed attributes will relate to the mobility characteristics and the location will help in determining a bio-inspirational source through the use of the fitness score. It should be noted that the presented mission describes a fictional scenario based on factual information.

Mission Description

The public of Edmonton Canada, in the province of Alberta, have shown great concern in regards to the number of yearly hikers within the Boreal Forest, particularly those needing assistance in terms of injuries and search and rescue abilities within the dense tree growth. Alberta does have its own search and rescue teams; however, the compact forest does provide challenges to movement, both on the ground with individuals and dogs, and above it with helicopters or planes. The Province of Alberta would like to request the design and implementation of a small UAV like vehicle that is capable of moving through the forest terrain. The vessel should be able to achieve relatively high speeds and carry camera payloads allowing search and rescue teams to visually inspect more area and cover more terrain that may be harder to reach on foot or harder to see from that air above.

The following list describes the overarching mission requirements.

- Mission Objective: Help search and rescue crews function in dense terrain.

- Working Environment: Taiga forests
- Task: Carry camera used to visually inspect terrain
- Payload: 3-5 pound camera and equipment

The ASMA program will be used to generate bio-inspired design possibilities to meet the specified mission requirements. To do so, the calculated mobility characteristics have been modified to focus on a design specific to the taiga environment and the specific mission requirements. For this example, there will be a total of seven mobility characteristics: lift, glide angle, volume, wing loading, rate of climb, thrust, and weight. These represent both characteristics and restrictions, and with this idea, the user will need to know certain mission requirements for this method to be beneficial. A list of these requirements are listed below:

- Basic components of the complex working environment
- Customer requirements specifying needs or wants from the product
- Engineering specifications, given as mathematical descriptors in an equation format

For the first requirement, the user should be aware of where the mission would be taking place. Specifically the user should know details about the basic environmental components, from which the complex environment is comprised. This information is furthered through the use of the ASMA database which details measurable specification values specific to each environment type and location.

The user should be clear about the customer needs and vehicle requirements needed to function within the mission environment. These needs and requirements are the driving force behind the engineering specification used to determine the mobility characteristics.

The engineering specifications are mathematic descriptions of the mobility characteristics used to define how an animal, used as a possible inspiration, may function within an environment. These descriptors are the bridge between biological and engineering terminology.

For this example, there will be three modifications to the mobility characteristics that were used in the bio-to-mechanical validation tests. The first restriction will be a restriction on the volume of the vehicle to compensate for the dense forest environment. This volume restriction will replace the dive mobility characteristic, as the function of a dive is irrelevant for this mission. The volume will be determined by using the width, length, and wingspan of the animal. The width will be used to determine the height variable, as it is representative of the “thickness” of the animal. This volume is portrayed in Figure 17, below,

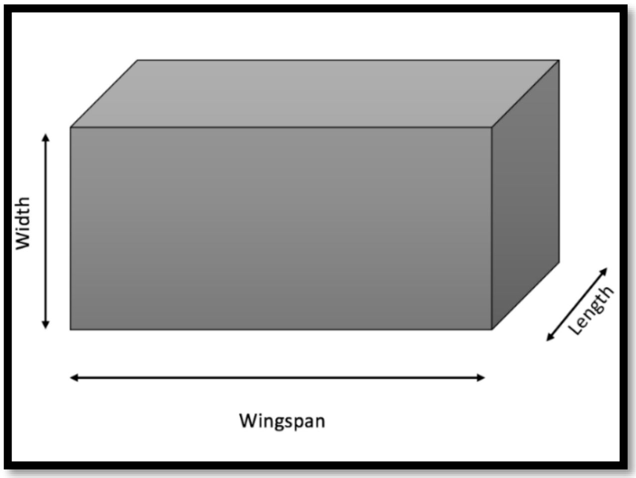


Figure 17: Volume box describing animal volume approximation

Determining the volume by assuming a rectangular shape will result in a maximum volume that can be ranked based on desiring a minimum value.

The second restriction will be focused on the turning radius of the vehicle. Since this is already evaluated under the soaring mobility characteristic, as is wing loading, these equations will remain the same.

Finally, a weight restriction was added to the desired mobility characteristics, focusing on minimizing the weight of the desired vehicle design and therefore evaluating bio-inspirations with the same constraint.

The following table, Table 23, displays the fitness scores for each investigated animal inspiration.

Table 24: Mechanical-to-Bio Validation Fitness Scores

Animal Designation	**Animal**	**Fitness Score**	**Rank**
A1	Owl	3988.099	4
A2	Eagle	18094.894	3
A4	Penguin	18379.657	2
A5	Frigate	125255.103	1

The fitness scores indicate the frigate bird shows a stronger correlation strength compared to that of the other animals. The eagle and penguin display similar results, and with that it can be predicted that these animals my achieve a similar final score, unless a drastic difference in mobility is establish through the mobility characteristics calculations.

The following table, Table 24, displays the ranking values determined for each animal and their respective mobility characteristic. The mobility characteristics were ranked from 1 to 4, 4 being the highest score and representing the most desirable numeric mobility value.

Table 25: Mechanical-to-Bio Validation Ranking Scores

	A1	A2	A3	A4
Lift	3	4	1	2
Glide Angle	1	2	4	3
Volume	3	1	4	2
Wing Loading	1	3	4	2
Rate of Climb	2	4	1	3
Thrust	4	3	1	2
Weight	4	1	2	3
Totals	18	18	17	17

The results for the ranking scores displayed that the owl and eagle tied, as did the penguin and frigate bird. These tied values are also only one ranking point away from one another, leading to the idea that all of these creatures may be valid inspirational sources. Yet, without looking at the final scoring, which incorporates the calculated fitness scores, these values may misinform a designer to a less optimal solution.

Final scores were determined by combing the fitness scores and the ranking scores together, via multiplication. The final, normalized, scores for the examined animals are listed below.

Table 26: Mechanical-to-Bio Validation Final Scores

Animal	**Final Scores**	**Normalized Scores**	**Rank**
Owl	71785.78	0.033713	4
Eagle	325708.1	0.152962	3
Penguin	312454.2	0.146738	2
Frigate	2129337	1	1

The final scores depict that the frigate bird was the most viable option in terms of a possible bio-inspiration for the taiga search and rescue mission. The penguin and the eagle displayed similar scores and therefore if one is to be considered, the other should be evaluated further as well. As with the previous example, a Monte Carlo simulation was completed using the simulated animal specifications. The results of this analysis are displayed in Annex C. The results demonstrate the bounds of the 95 percent confidence intervals for each mobility characteristic and the probability of achieving a specified mobility characteristic, with a specific magnitude.

4.6.3 Biomimicry Validation Results

The bio-mimicry validation test involved comparing the stingray and the Aqua Ray, developed by Festo [176], along with other animals which are also used in the other validation tests. The Bio-mimicry example will look at how similar a stingray and its mechanical equivalent are predicted to be. As with the other presented validation examples, the fitness score for each animal must first be evaluated in terms of the chosen working environment. The working environment for this example is a reef, as stingrays commonly inhabit reefs. The fitness scores for the seven animals and the Aqua Ray are displayed in Table 26 below:

Table 27: Biomimicry Validation Fitness Scores

Animal Designation	Animal	Fitness Score	Rank
A1	Owl	213003.357	8
A2	Eagle	712508.820	6
A3	Orca	171870641.986	2
A4	Penguin	579082.751	7
A5	Frigate	4091191.078	5
A6	Seal	64242881.415	4
A7	Stingray	169579881.660	3
A8	Aqua Ray	203056585.925	1

The fitness scores, displayed above, It can be seen that the Orca, the Stingray, and the Aqua Ray all display significantly higher fitness scores than the rest of the animals within the comparison and this was the same in the mechanical to bio validation example, where the test case was the Seabreacher. It is believed that the similarities between environments may be the cause. The reef and the deep open ocean environments display many of the same traits, in terms of environmental specifications.

This may include the pressure, salinity level, the fluid speed, and the density of the fluid. Such strong similarities will drive the correlation matrix to result in a similar score.

After the fitness scores are determined, we as the designer must then evaluate the calculated mobility characteristics for each of the chosen animals, as done so in the previous validation tests. The following table, Table 27, presents the rankings of each mobility characteristic for each animal.

Table 28: Biomimicry Validation Ranking Scores

	A1	A2	A3	A4	A5	A6	A7	A8
Lift	7	2	5	1	3	8	6	4
Glide Angle	8	4	6	5	3	2	1	7
Terminal Velocity	6	3	4	7	2	5	1	8
Wing Loading	6	3	4	7	2	5	1	8
ate of Climb	2	5	7	1	8	6	3	4
Thrust	7	2	1	3	5	6	8	4
Totals	6	19	27	24	23	32	20	35

It can be seen in Table 27 that the Aqua Ray did not in fact score the highest, and instead the animal with the highest score was the owl, however only did so by beating the Aqua Ray by one point. The owl is predicted to outperform the Aqua Ray in lift generation, achievable glide angle, and thrust. The owls dominance in these mobility categories was enough to gain the points needed to obtain its higher score. In comparison, the orca and the seal scored significantly lower than the other aquatic animals and the Aqua Ray.

As before, the totaled mobility characteristics scores were multiplied by the fitness scores to attain the final scores, displayed in Table 28:

Table 29: Biomimicry Validation Final Scores

Animal	Final Scores	Normalized Scores	Rank
Owl	1278020.142	0.00018	8
Eagle	13537667.58	0.001905	7
Orca	4640507334	0.652951	2
Penguin	13897986.02	0.001956	6
Frigate	94097394.79	0.01324	5
Seal	2055772205	0.289261	4
Stingray	3391597633	0.477221	3
Aqua Ray	7106980507	1	1

Table 28 shows that the Aqua Ray outperformed all the animals considered for this example, leading the second highest scorer by over 15 points. It can also be seen that the owl, which had scored the highest in the mobility ranking system, fell to last place as the respective fitness score was relatively low in comparison to the other animal fitness scores. This ranking example suggests that not only is the stingray a valid bio-inspiration, but also that the orca and even the seal may also produce viable inspirations for design.

4.7 Conclusion

Based on the results from the validation tests, it can be concluded that the ASMA algorithm can conduct simulations for bio-to-mechanical, and biomimicry design processes. The bio-to-mechanical and the biomimicry test results showed promise in that the fitness scores tended to show trends with similar scoring between the biological organisms and the respective mechanical counterparts. This score will continue to become more refined as more information becomes available and as the considered specification values, for both the environments and the animals, increase. The overall ASMA results are presented in the following table.

Table 30: ASMA methodology validation results

<table>
<tr><th>Bio-to-Mechanical
Deep Ocean Environment</th><th>Mechanical-to-Bio
Taiga Environment</th><th>Biomimicry
Reef Environment</th></tr>
<tr><td colspan="3">Observations</td></tr>
<tr><td>ASMA can evaluate both animals and bio-inspired watercrafts
ASMA did not produce the same scores between Orca and Seabreacher, however trend is present</td><td>ASMA can evaluate animals based on a mission and its corresponding requirements.
Customer requirements can be represented as mobility restrictions</td><td>ASMA can evaluate both animal sand biomimicry robots
ASMA did not produce the same scores between a stingray and the Aqua Ray, however trend is present</td></tr>
<tr><td colspan="3">Discrepancies</td></tr>
<tr><td>Propulsion type
Sizing</td><td>User defined mobility characteristics</td><td>Sizing
Velocity</td></tr>
</table>

The fitness scores for the bio-to-mechanical validation tests resulted in the Seabreacher scoring lower than its biological counterpart in terms of the mobility characteristics, and the Aqua Ray scoring 15 points higher in terms of mobility. The difference for both the Seabreacher and the Aqua Ray is made up when implementing the animal fitness scores back into the design process through multiplication against the ranking values. This part of the process resulted in the Seabreacher and the Aqua Ray placing first in their respective validation test scenarios. However, some discrepancies are worth noting. First, for the Seabreacher, the propulsion type used was that of a water jet and this is compared to the natural swimming motion of a whale. This, and the idea of little variation due to manufacturing may have been factors in the results of the similarity matrix, causing the Seabreacher to obtain the score that it did. Second, the Aqua Ray also had a much higher fitness score to that of its natural counterpart. This could be due to a lack of variation in terms of sizing and velocity because this also was a manufactured product. Even so, due to the high correlation, which directly represents how well the organism, mechanical or biological, is predicted to function within the working environment. Overall these validations have showed successful demonstrations of the ability of the ASMA program.

The mechanical-to-bio validation test resulted in similar mobility characteristic ranking values, which were offset by the implementation of the fitness scores, making the final scores easily interpreted. The results suggested that the frigate bird should be used for a possible bio-inspiration, based on the calculated mobility characteristics. This validation test, unlike the others, used more specific mobility characteristics, characteristics more related to the described mission. This demonstrated the ability to reconstruct the mobility analysis to fit the parameters of a given mission. This example also displays the discrepancies between results and user information, in that the ASMA algorithm is limited by user knowledge. This limitation applies to both mobility characteristic equations and animal and environmental specification values. Overall this demonstration of the ASMA methodology has been successful and relates the importance of the need for continuing to gather information for the ASMA method.

4.8 Future Work

The future work for this project should involve the completion of two tasks. First, this project should focus on continuing to build up the animal and environmental database. During the mechanical-to-bio example presented in this work, it was demonstrated that the mobility characteristics could be changed, or added to, and it is believed that the same should be capable in regards to the examined animals and environments. The more variability that can be built into the system, the more opportunity a user may have to explore relevant information. Second, it is believe that more information could be determined through solid modeling of various animals. In particular, solid models may give better incite to functionality to different aspects of the animal such as the shape and texture of a wing or fin, and the joints within these appendages. Solid models will give way to more accurate specification values, ones that may be tested and validated in a wind or water tunnel.

Annex A

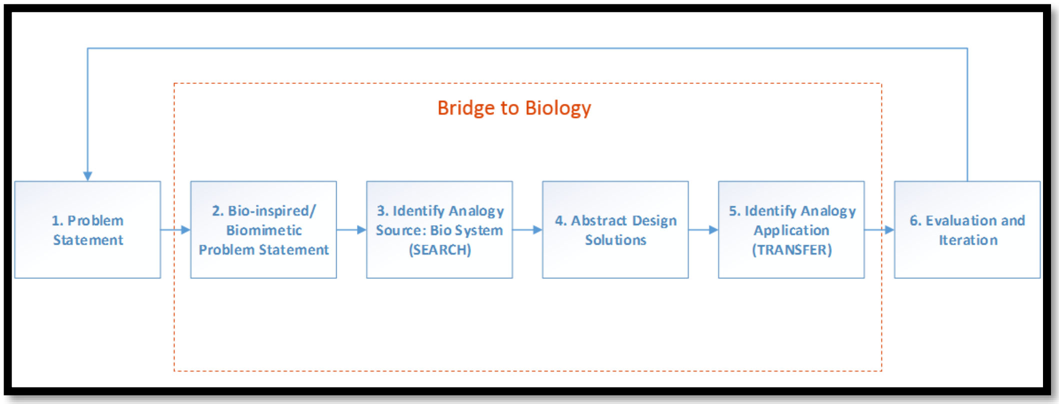


Figure 18: Bridge to Biology Diagram

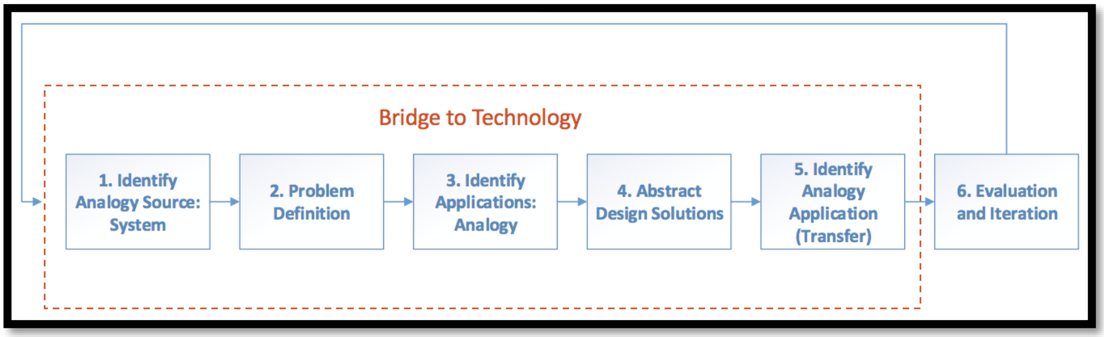


Figure 19: Bridge to Technology

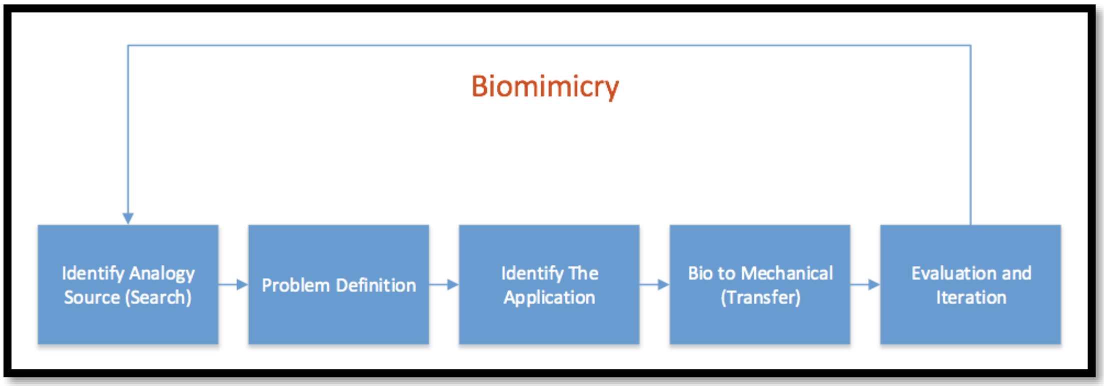


Figure 20: Biomimicry Process Diagram

Annex B

Bio-to-Mechanical Validation
Owl Mobility Characteristics

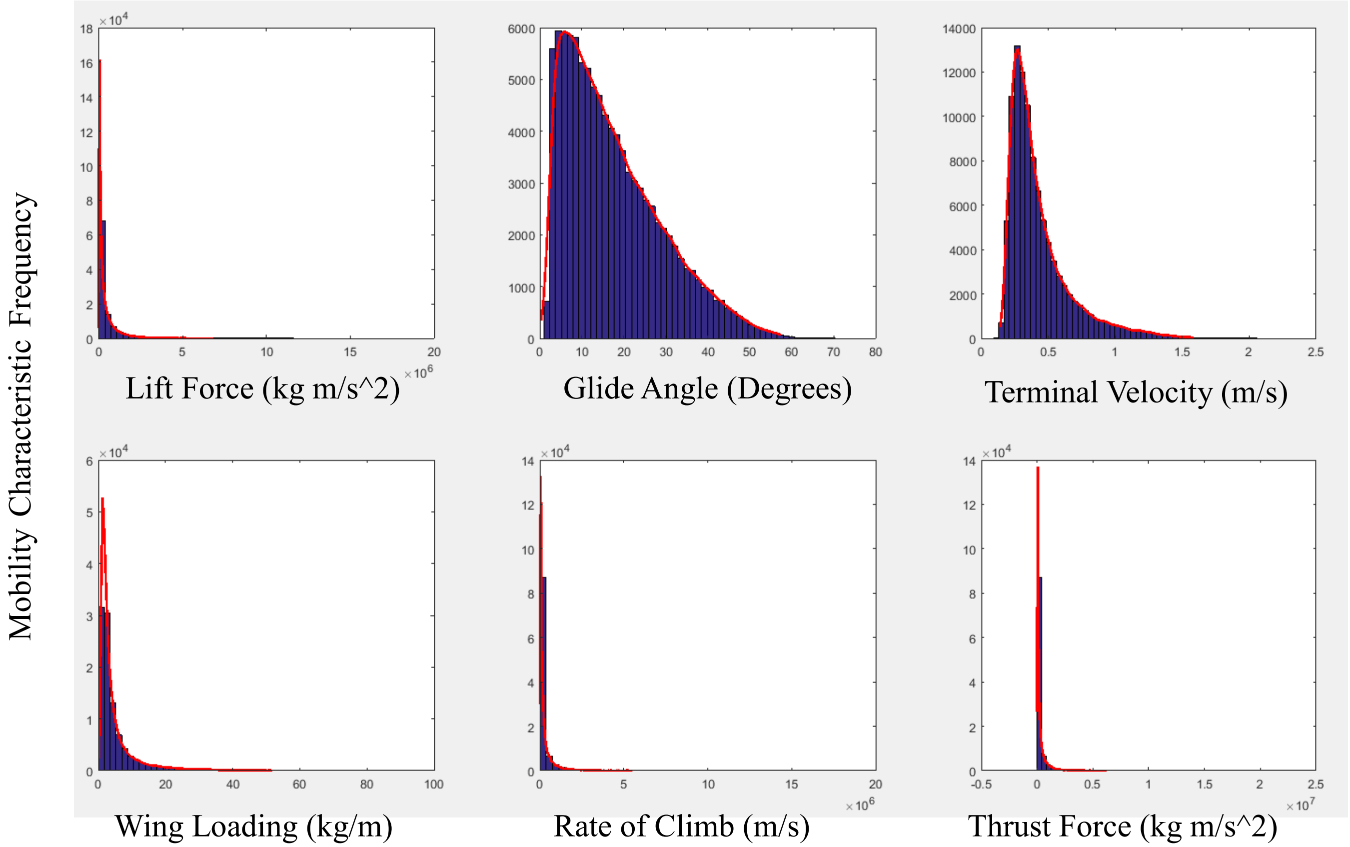


Figure 21: Bio-to-Mechanical Owl Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Eagle Mobility Characteristics

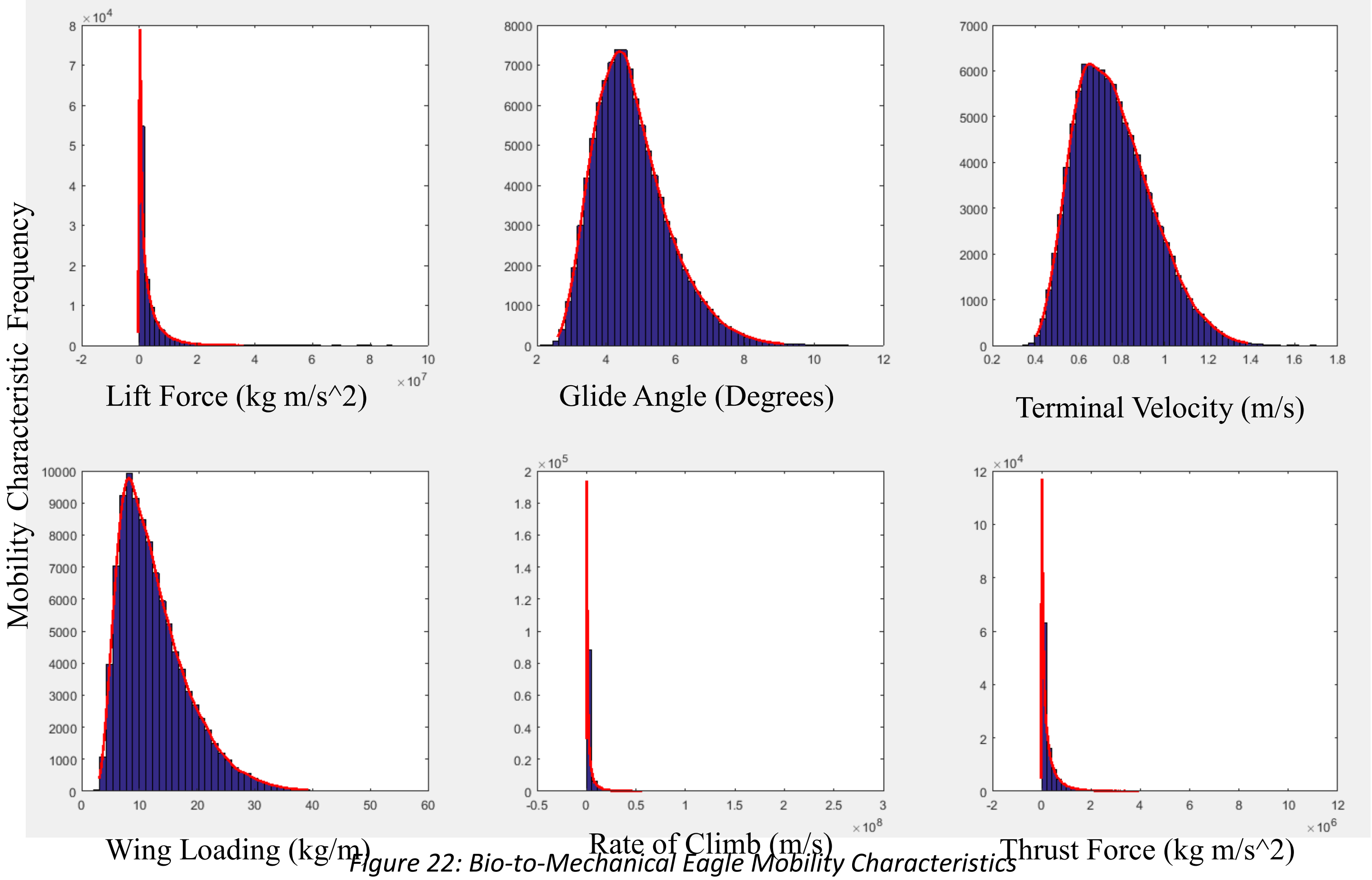


Figure 22: Bio-to-Mechanical Eagle Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Orca Mobility Characteristics

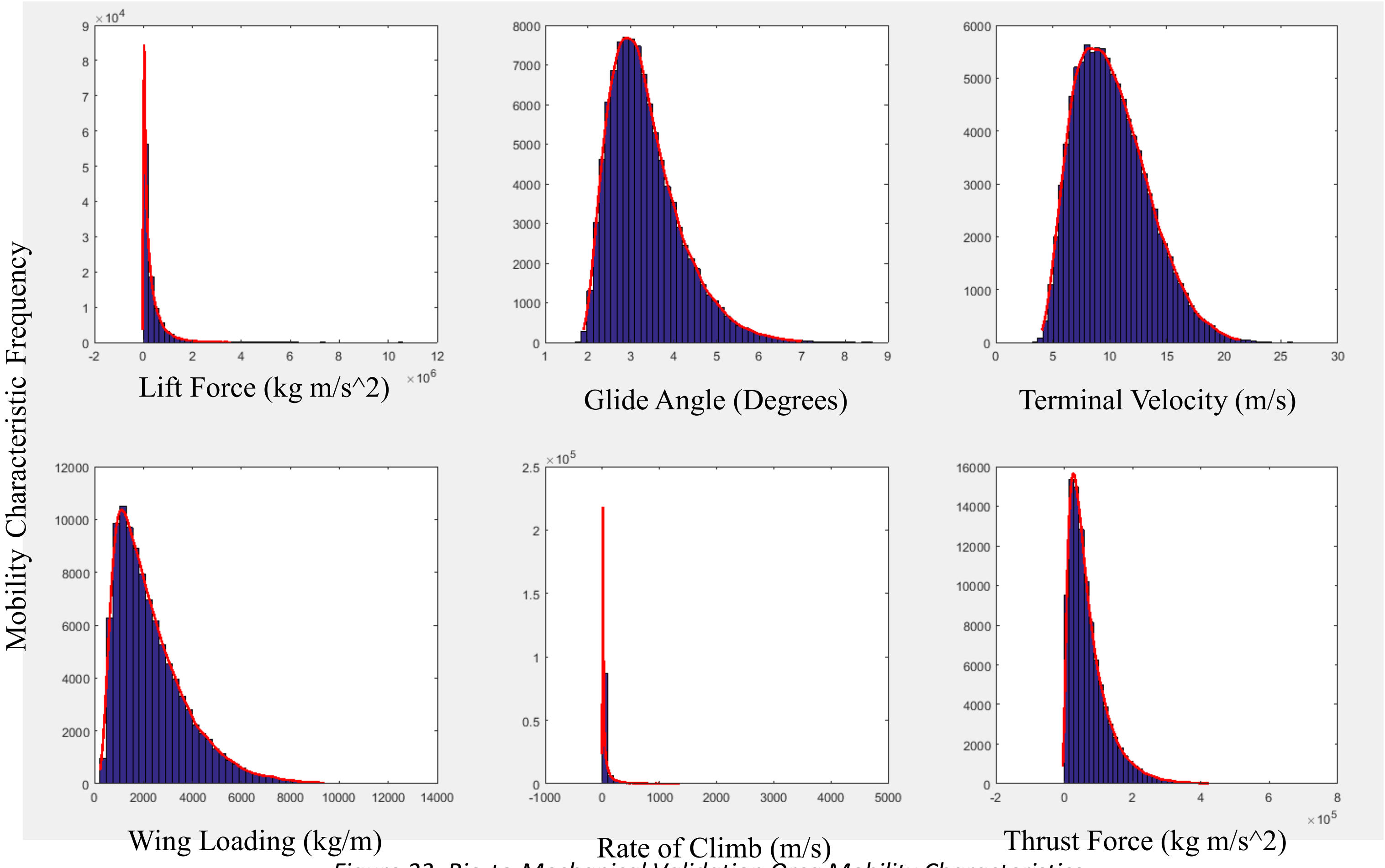


Figure 23: Bio-to-Mechanical Validation Orca Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Penguin Mobility Characteristics

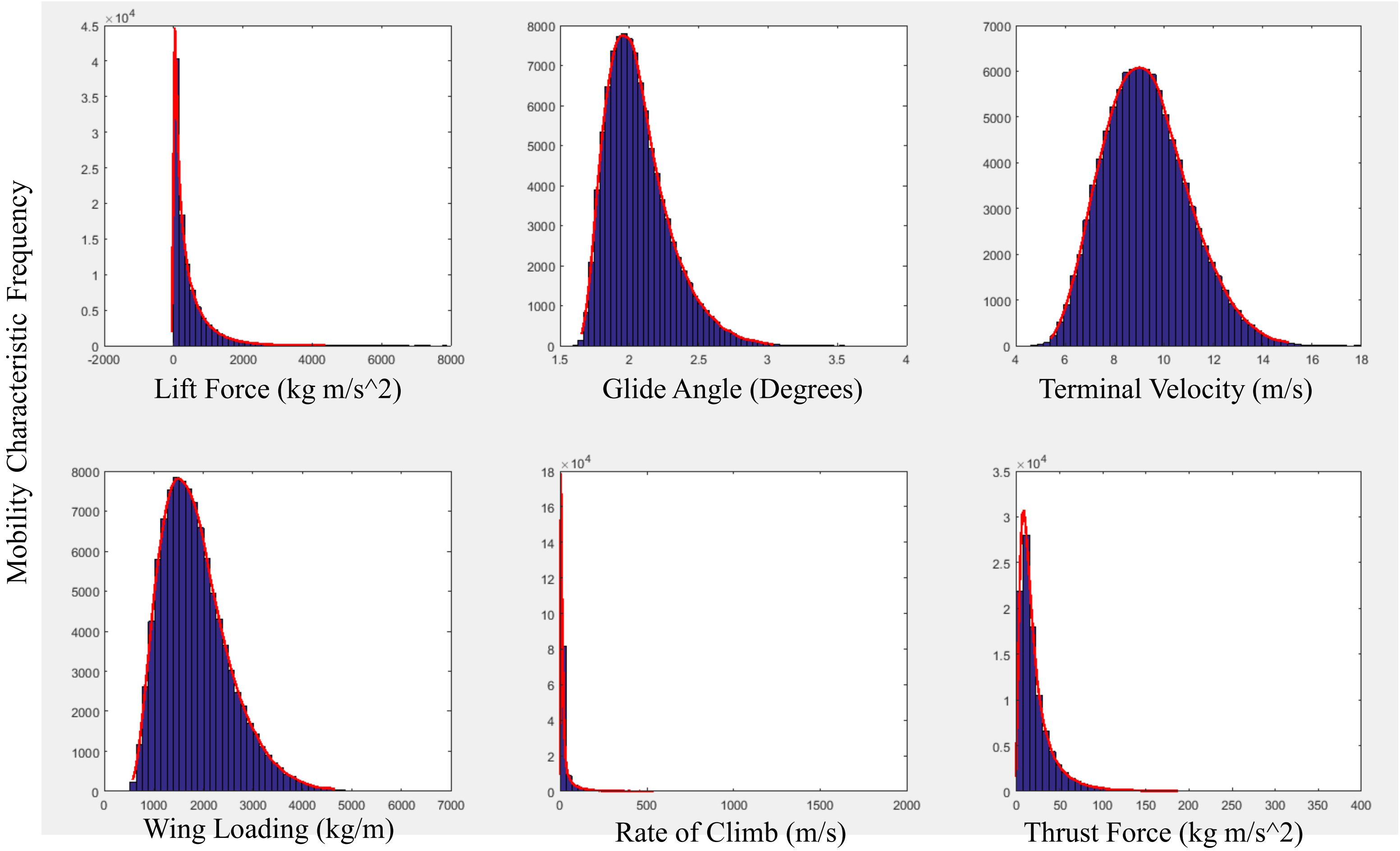


Figure 24:Bio-to-Mechanical Validation Penguin Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Frigate Mobility Characteristics

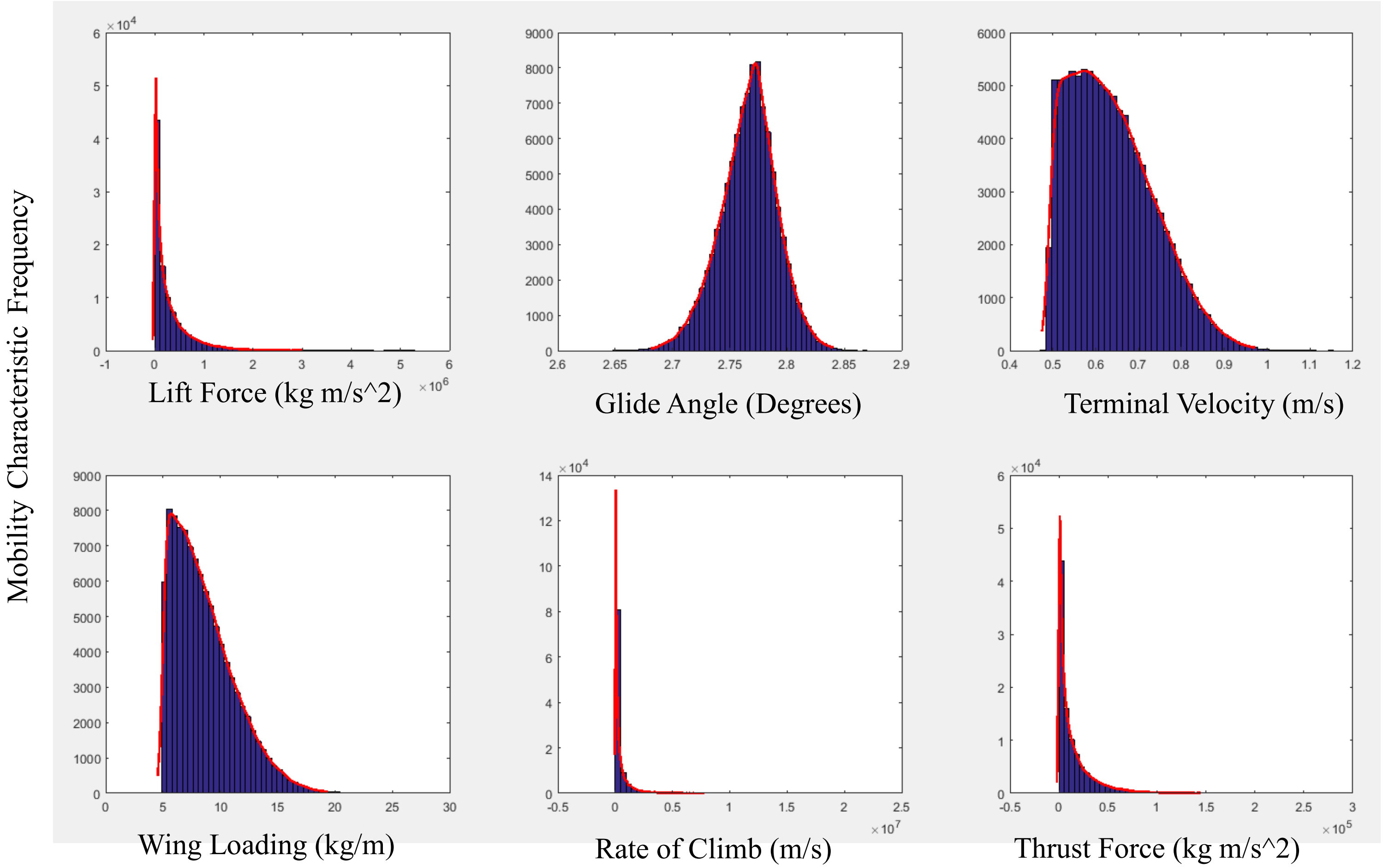


Figure 25: Bio-to-Mechanical Validation Frigate Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Seal Mobility Characteristics

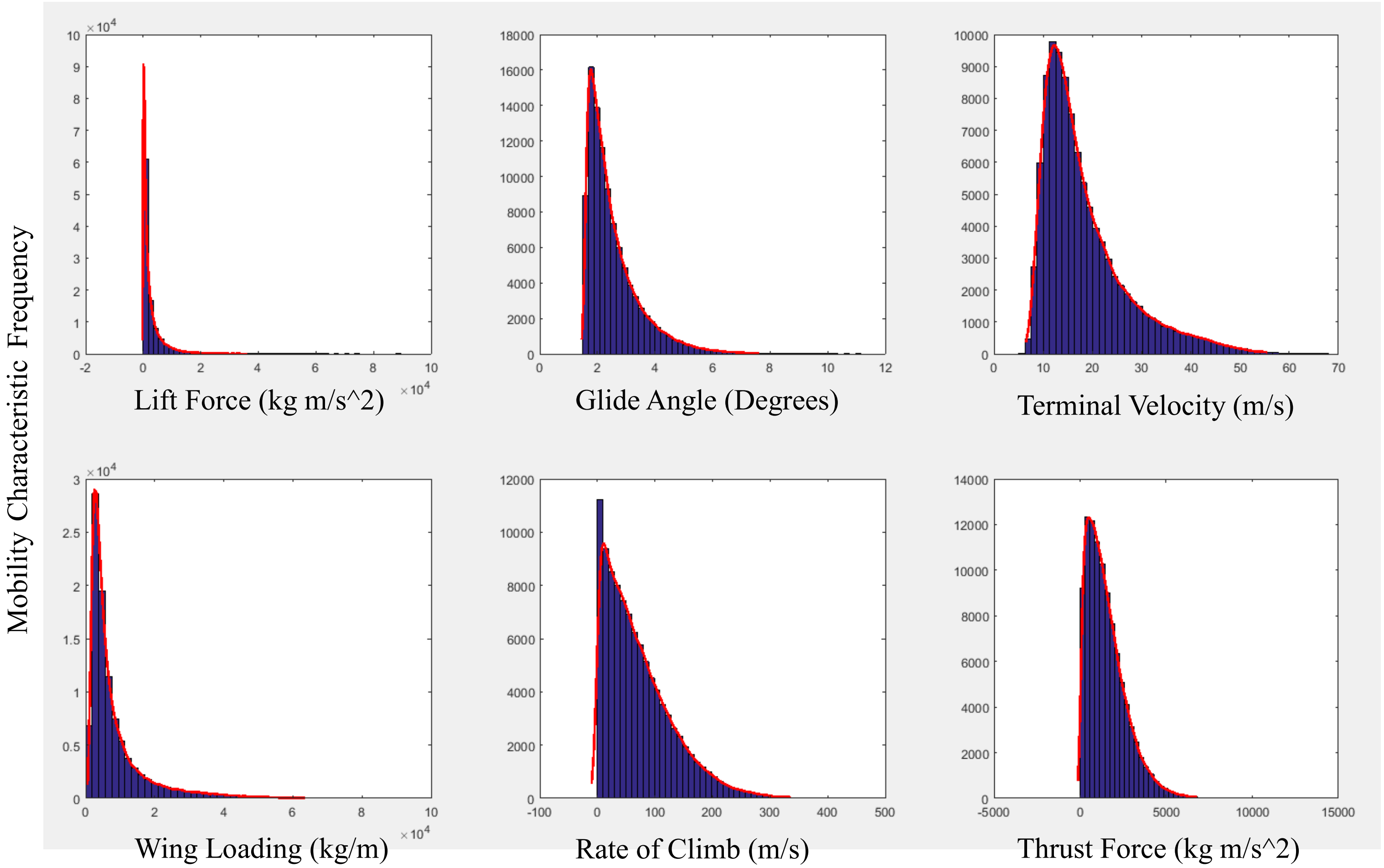


Figure 26: Bio-to-Mechanical Validation Seal Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Stingray Mobility Characteristics

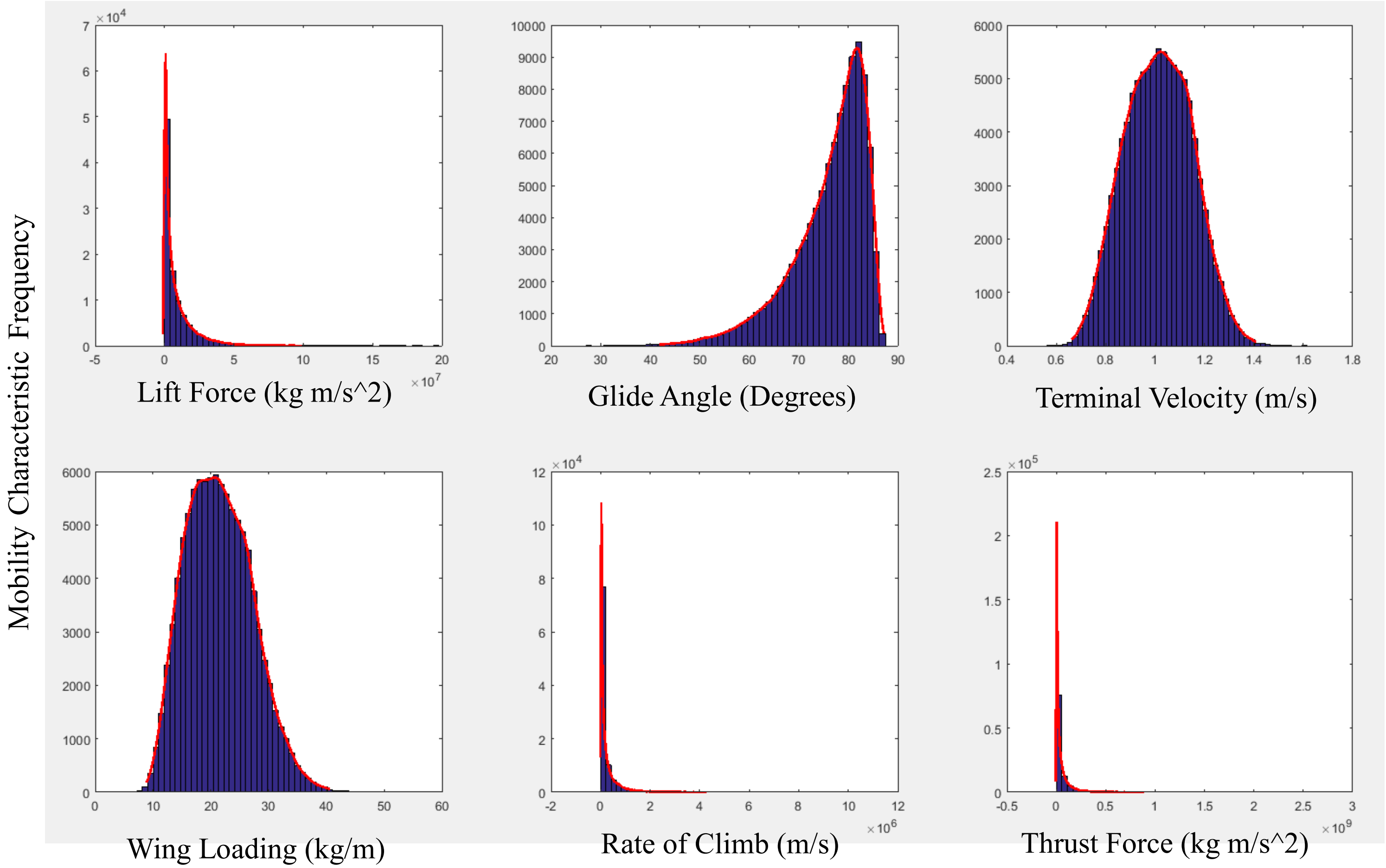


Figure 27: Bio-to-Mechanical Validation Stingray Mobility Characteristics

Annex B
Bio-to-Mechanical Validation
Seabreacher Mobility Characteristics

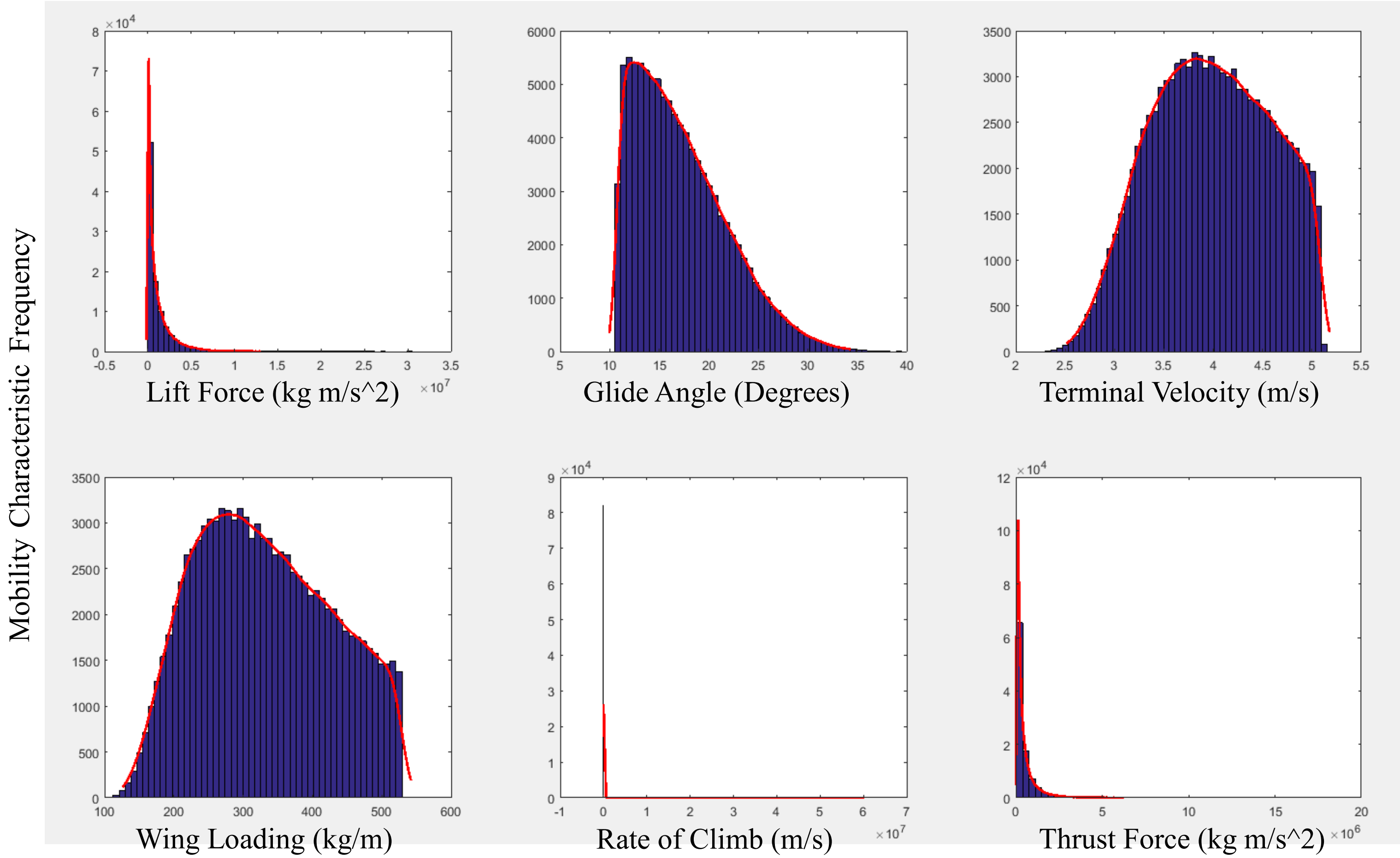


Figure 28: Bio-to-Mechanical Validation Seabreacher Mobility Characteristics

Annex C

Mechanical-To-Bio Validation

Owl Mobility Characteristics

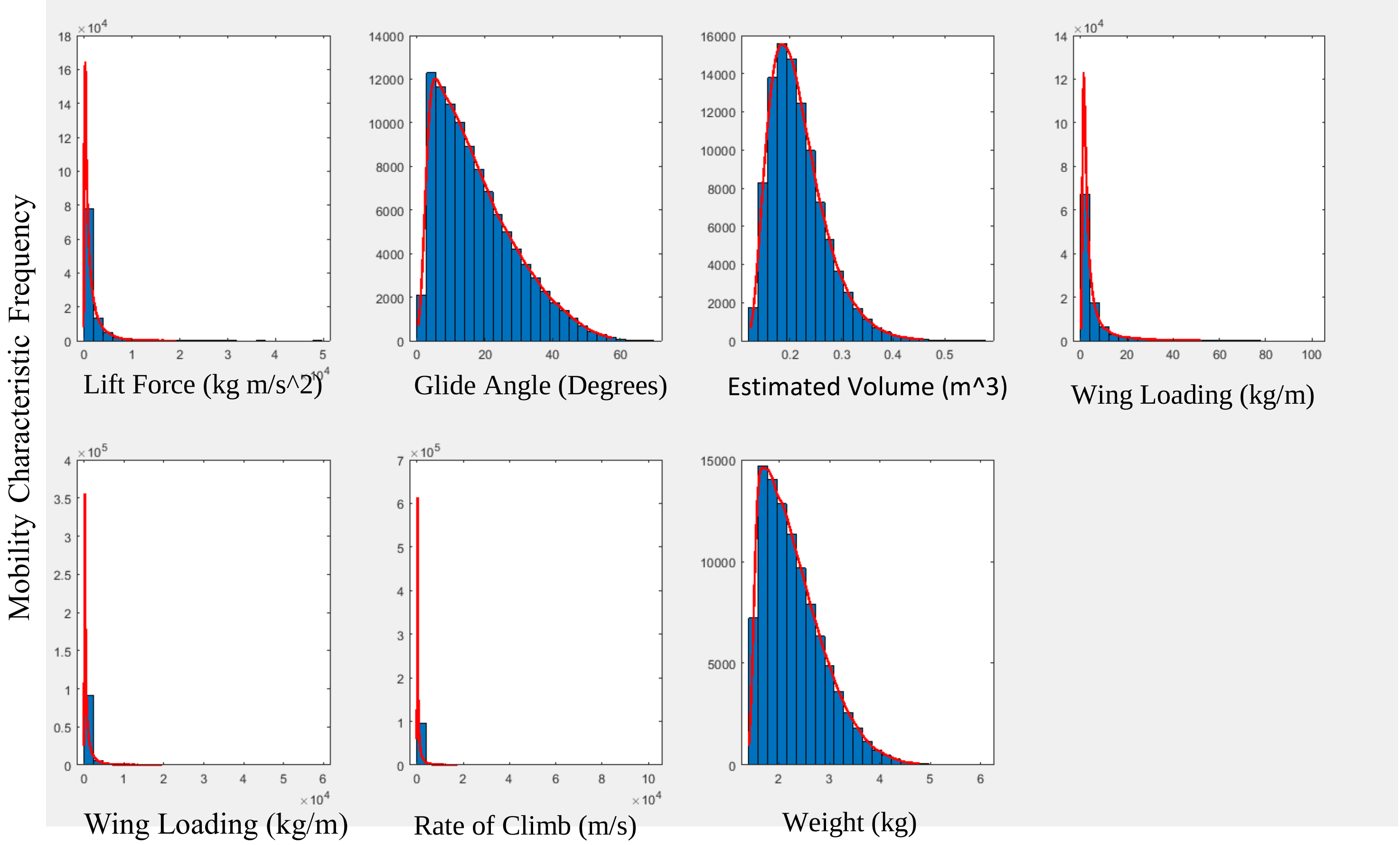


Figure 29: Mechanical-to-Bio Validation Owl Mobility Characteristics

Annex C
Mechanical-To-Bio Validation
Eagle Mobility Characteristics

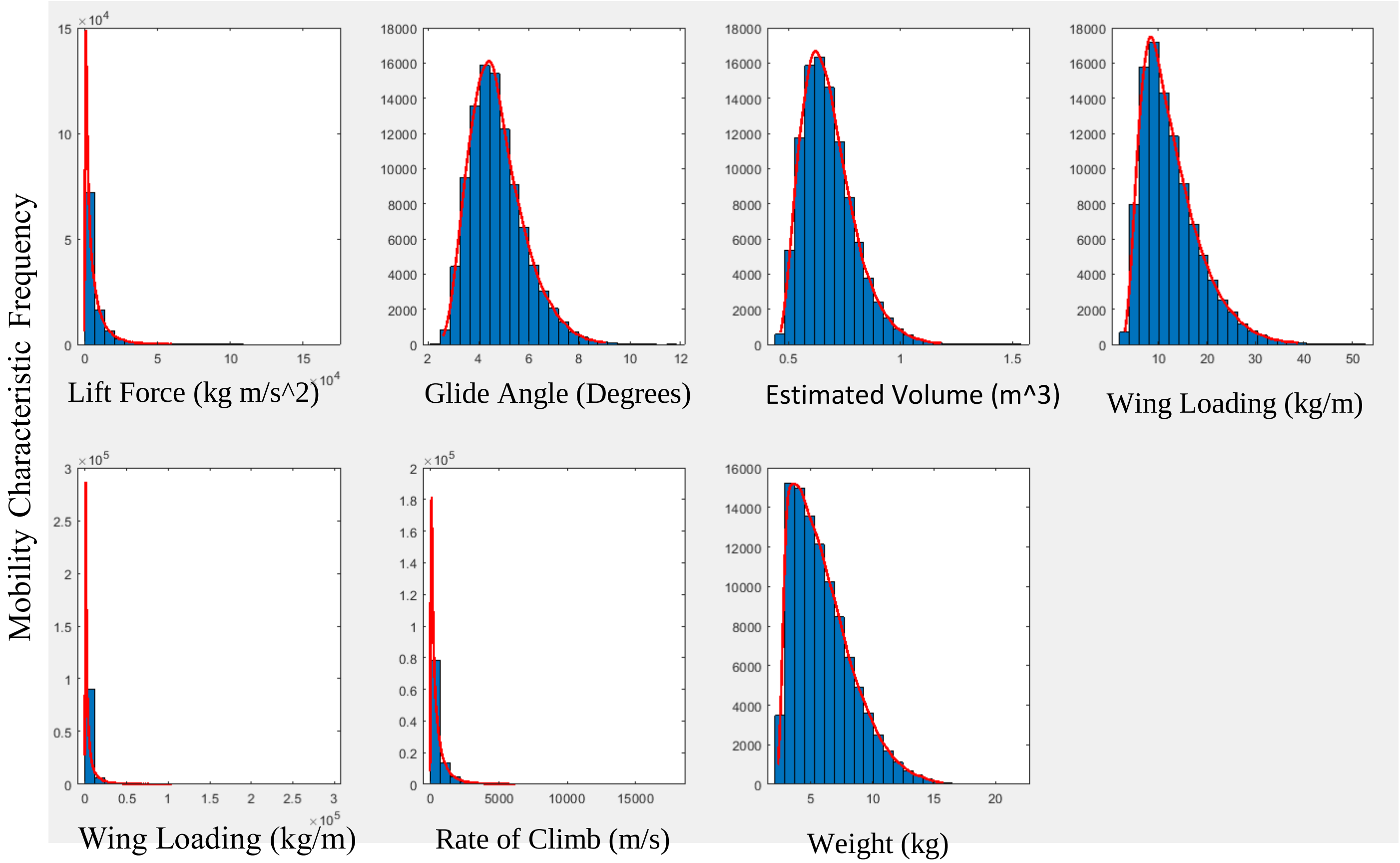


Figure 30:Mechanical-to-Bio Validation Eagle Mobility Characteristics

Annex C
Mechanical-To-Bio Validation
Penguin Mobility Character

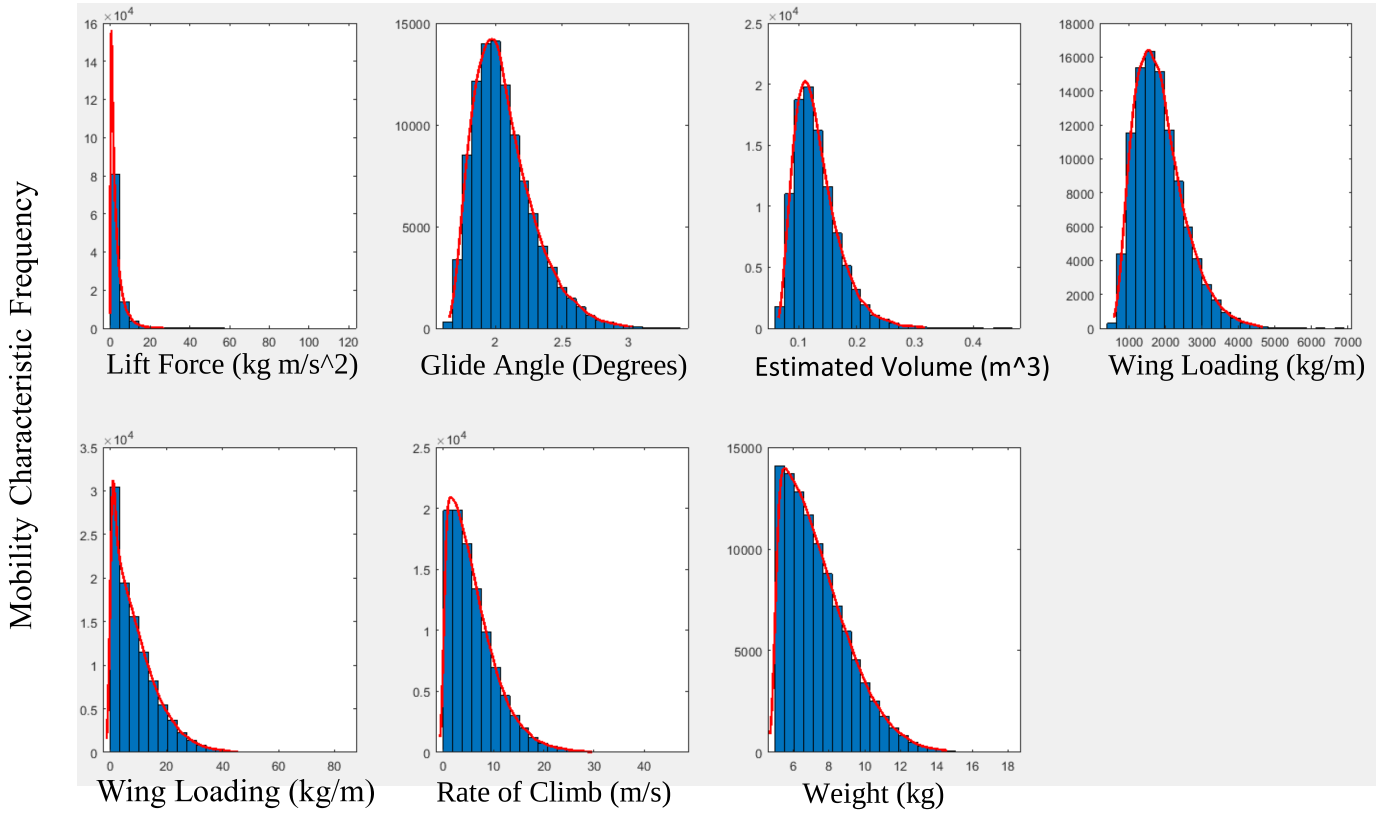


Figure 31: Mechanical-to-Bio Validation Penguin Mobility Characteristics

Annex C
Mechanical-To-Bio Validation
Frigate Mobility Characteristics

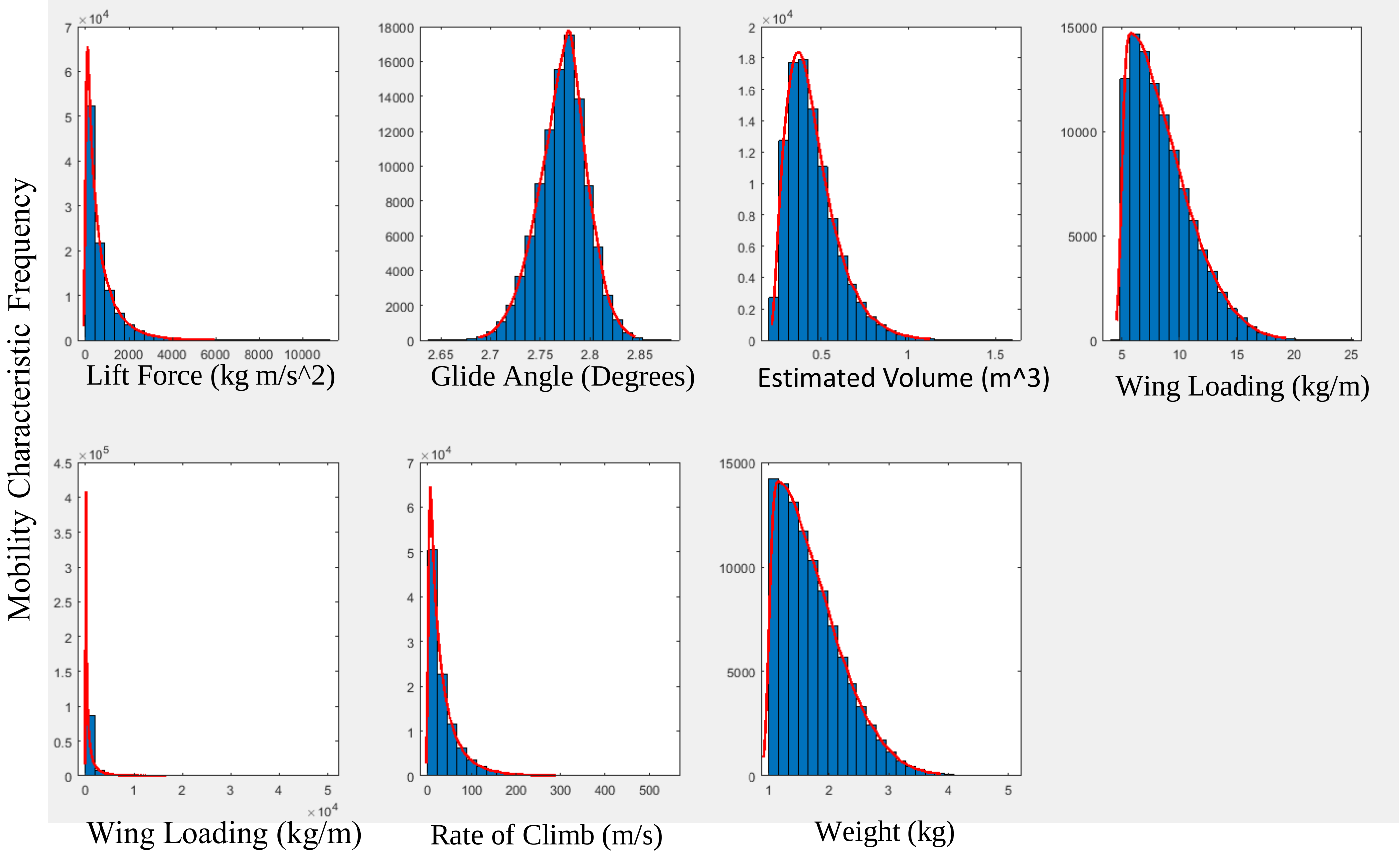


Figure 32:Mechanical-to-Bio Validation Frigate Mobility Characteristics

Annex D

Biomimicry Validation

Owl Mobility Characteristics

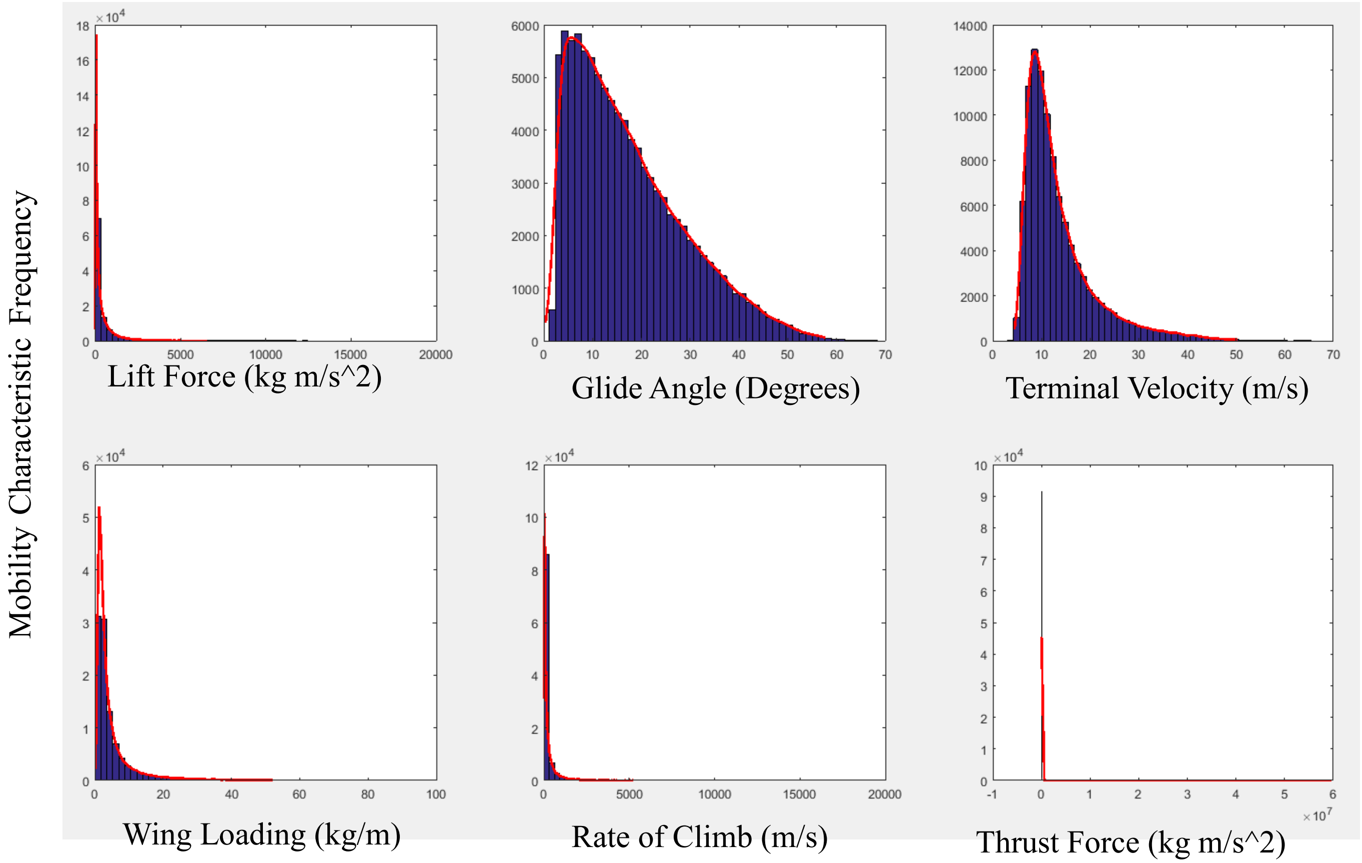


Figure 33: Biomimicry Validation Owl Mobility Characteristics

Annex D
Biomimicry Validation
Eagle Mobility Characteristics

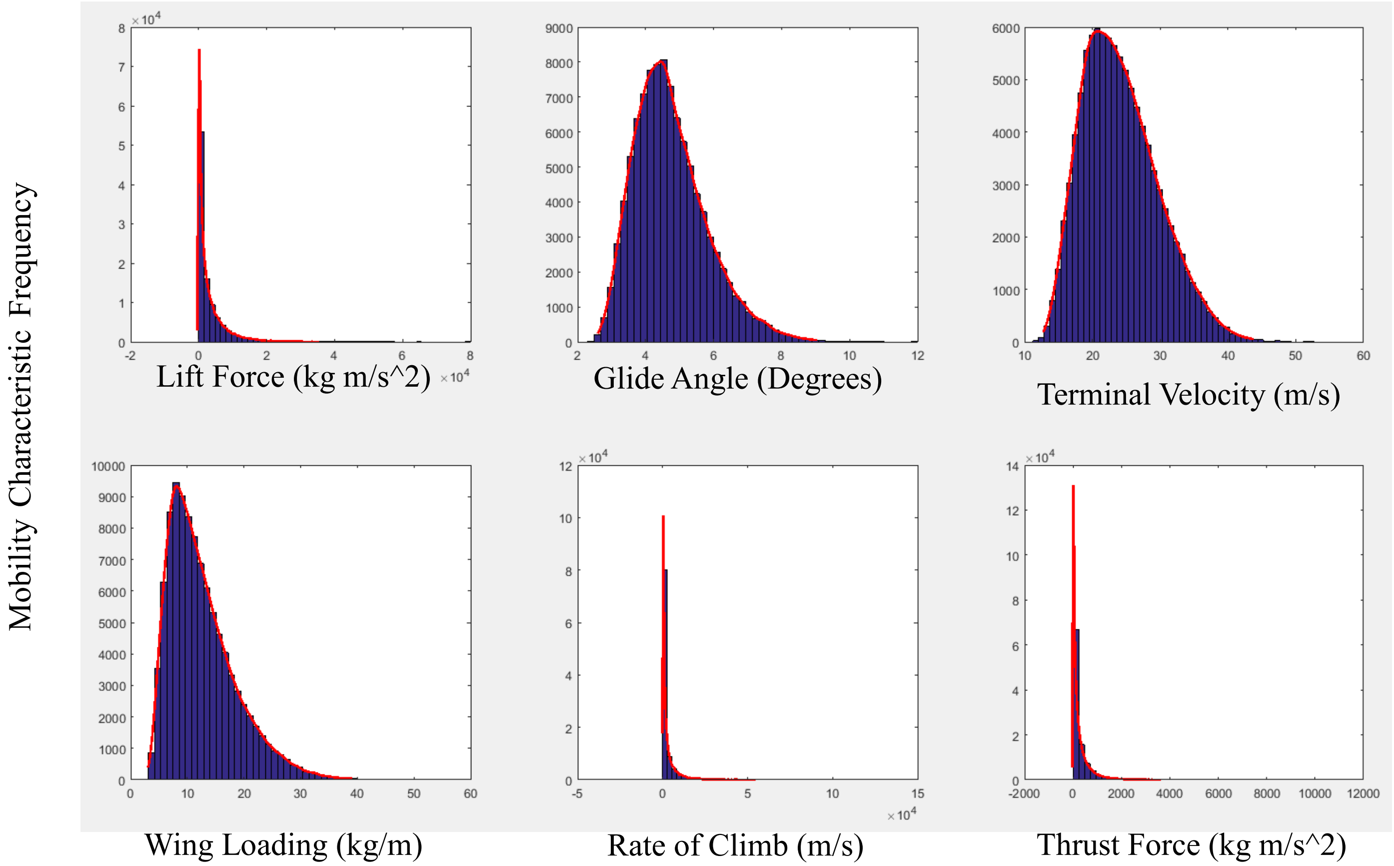


Figure 34: Biomimicry Validation Eagle Mobility Characteristics

Annex D
Biomimicry Validation
Orca Mobility Characteristics

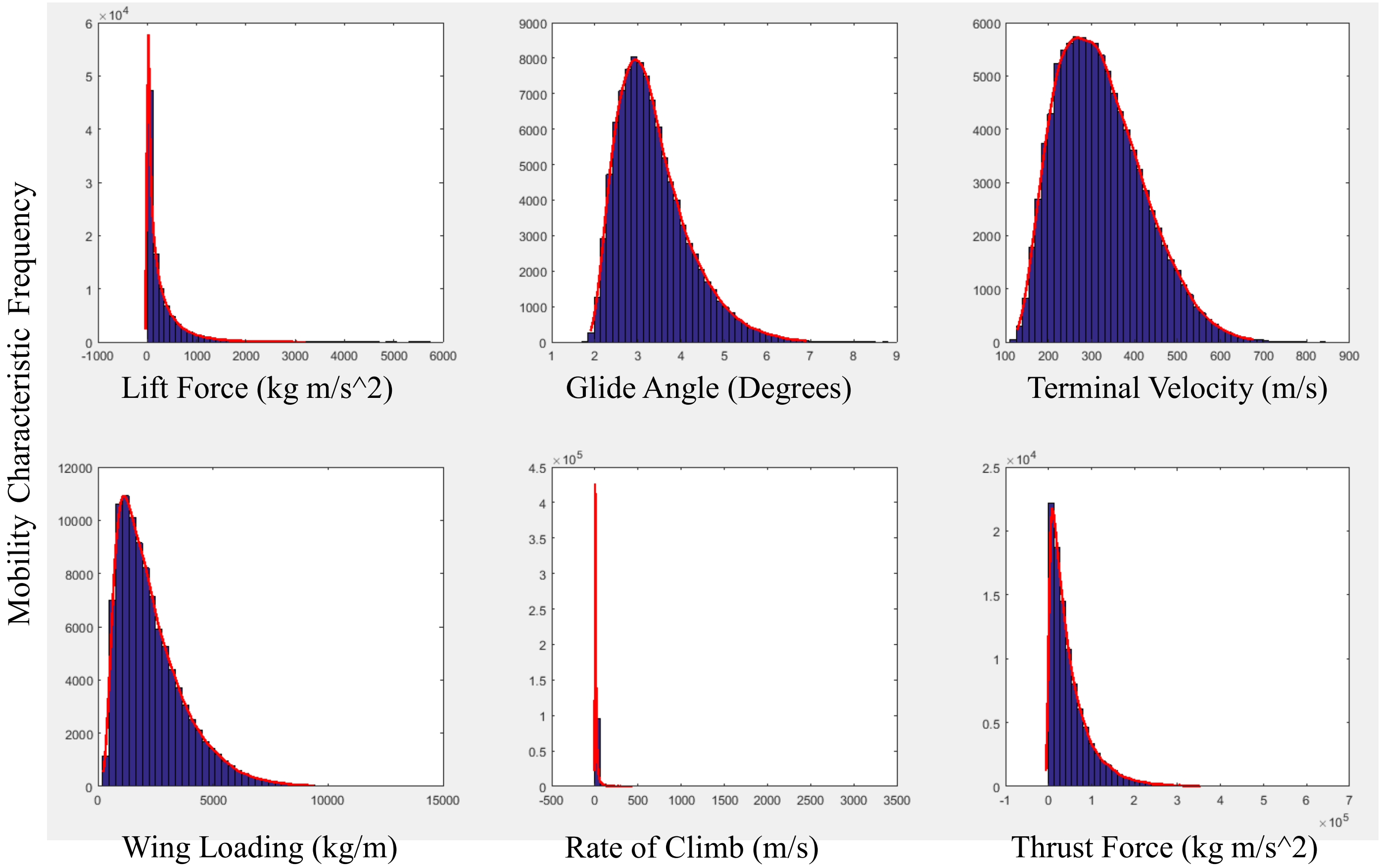


Figure 35: Biomimicry Validation Orca Mobility Characteristics

Annex D

Biomimicry Validation

Penguin Mobility Characteristics

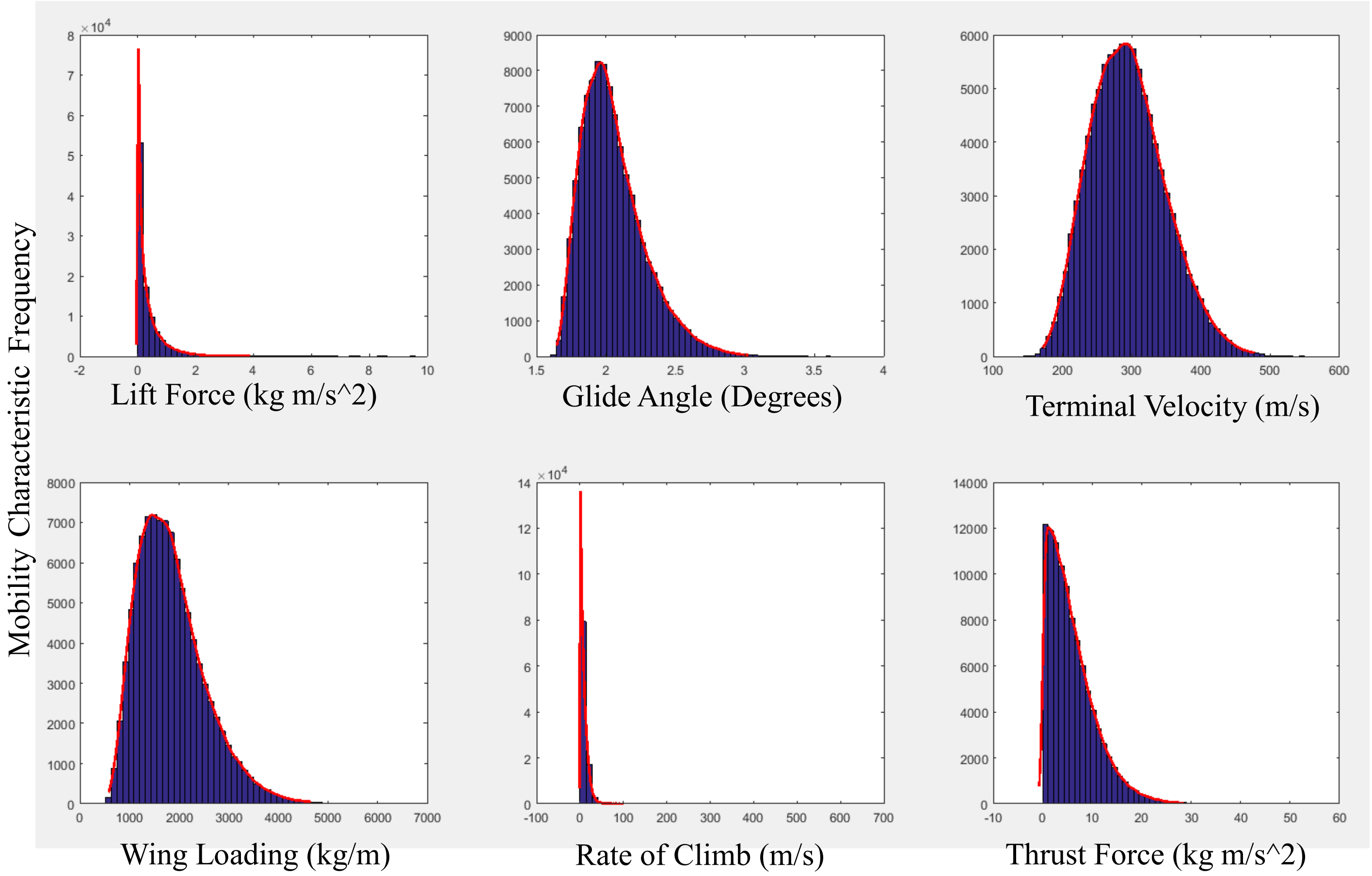


Figure 36: Biomimicry Validation Penguin Mobility Characteristics

Annex D
Biomimicry Validation
Frigate Mobility Characteristics

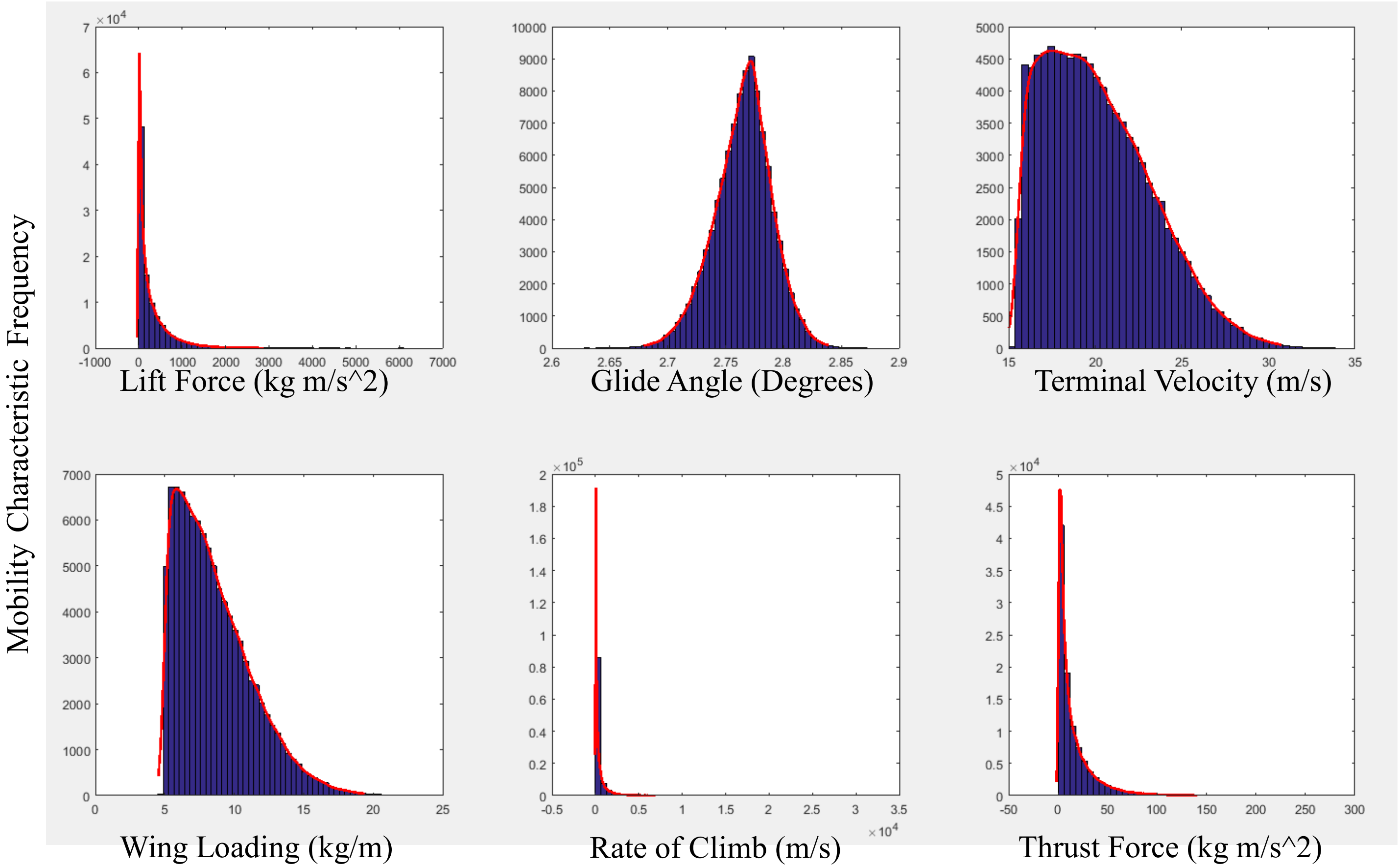


Figure 37: Biomimicry Validation Frigate Mobility Characteristics

Annex D
Biomimicry Validation
Seal Mobility Characteristics

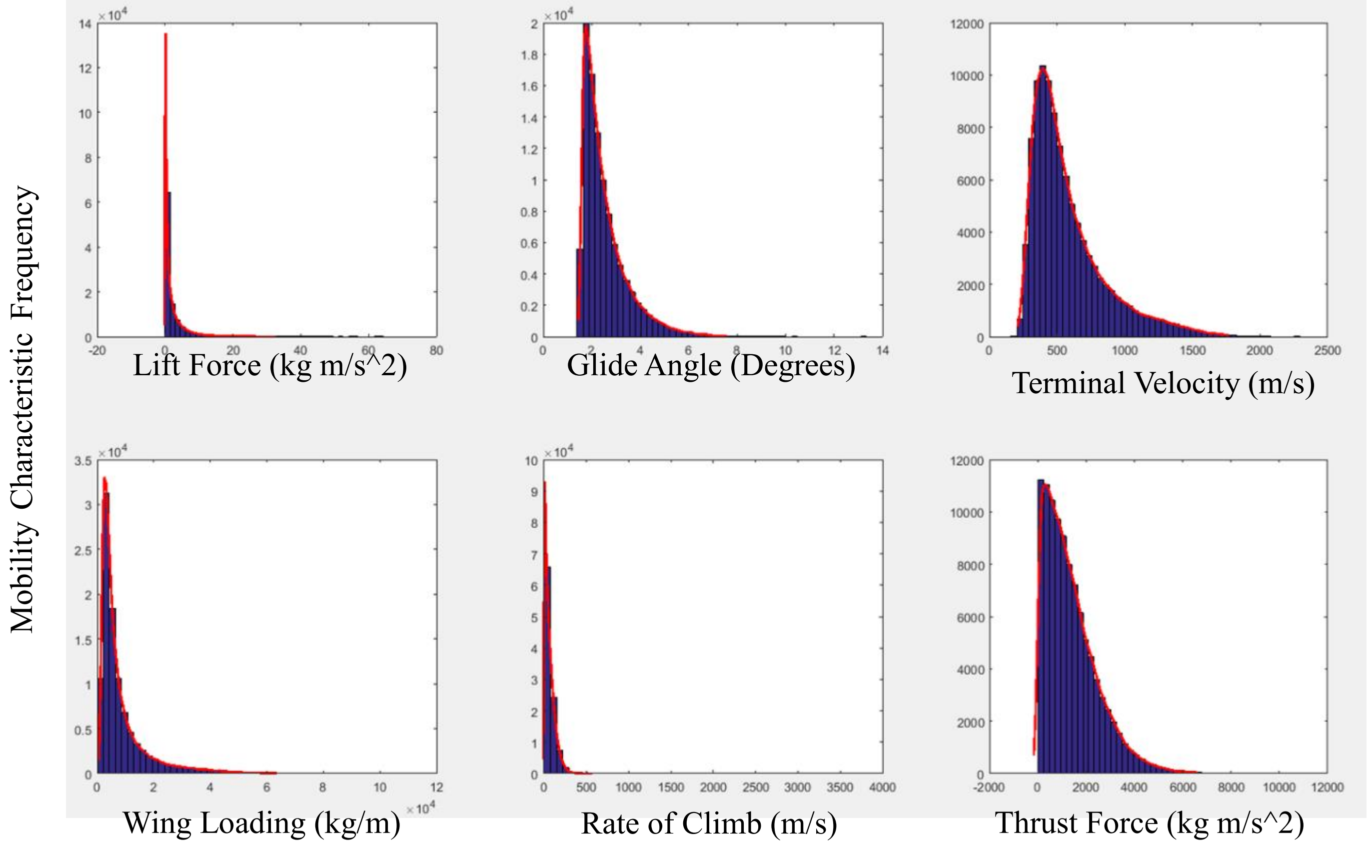


Figure 38: Biomimicry Validation Harp Seal Mobility Characteristics:

Annex D
Biomimicry Validation
Stingray Mobility Characteristics

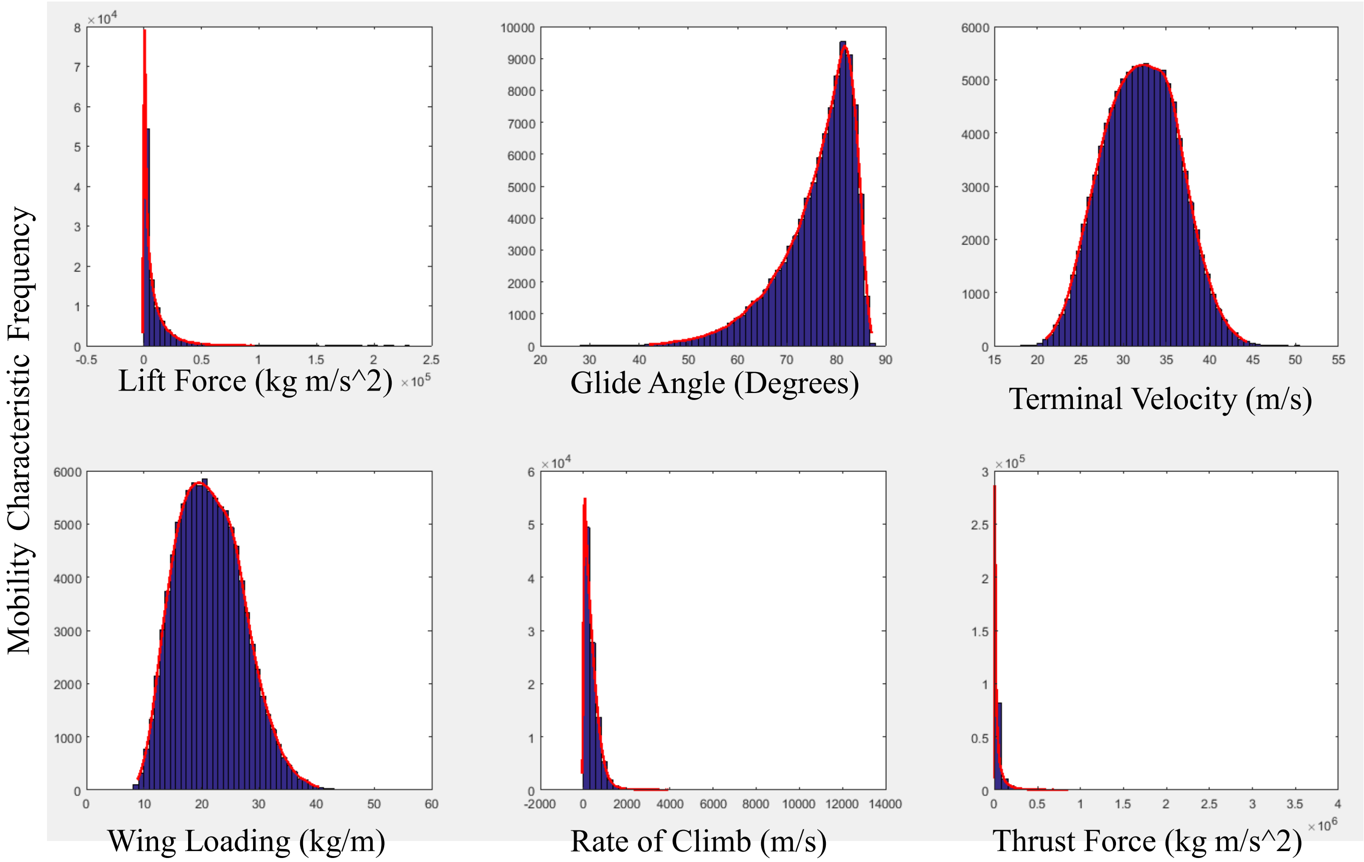


Figure 39: Biomimicry Validation Stingray Mobility Characteristics

Annex D
Biomimicry Validation
Aqua Ray Mobility Characteristics

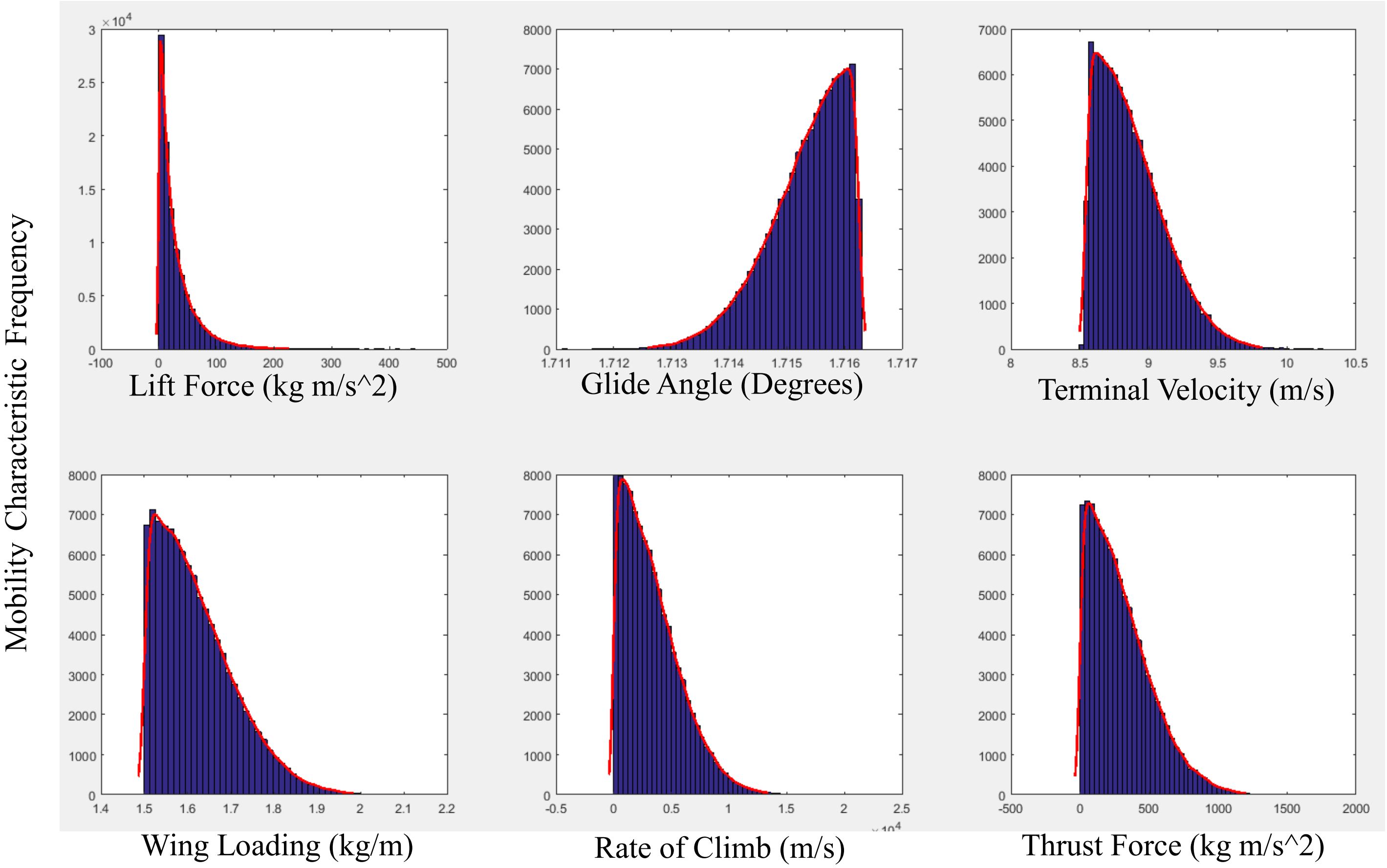


Figure 40: Biomimicry Validation Aqua Ray Mobility Characteristics

5. Code Discussion

This chapter will outline and discuss the Matlab code use for the proposed methodology. Discussion will consist of topics concerning why matlabwas chosen, the overall purpose of a function, and how key outputs were constructed within the Matlab code. The entire Matlab code may be viewed in the Appendix.

5.1 Matlab

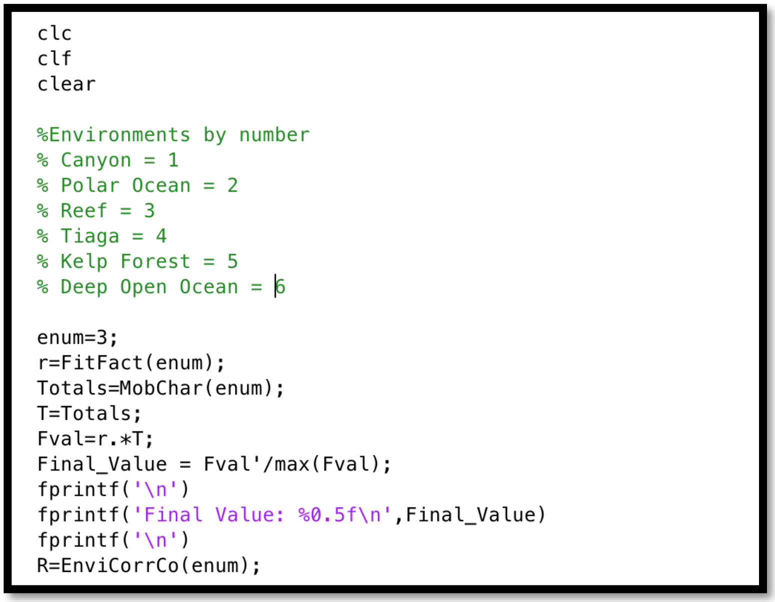
The program Matlab was used due to its usability and availability. Matlab is it common engineering software and also provide users with an interface in which several users may work on a script at one time. Matlab also provides a user-friendly GUI function, which proved useful when transferring the code, use for the project, to a more user-friendly interface.

5.2 All Code Test

The All Code Test script file was written when the individual script files were rewritten as function files. By calling the function files to one script file, it eliminates clutter and decreases the risk of a user accidentally changing the operation of a function.

5.2.1 Overall function

Originally, the Matlab code to use for this project what is written several strips files. These files for then turned into function files, which could be called via a script file containing each piece of various functions. An image of the Matlab script file that contains all the function files is shown below in Figure 41.



```
clc
clf
clear

%Environments by number
% Canyon = 1
% Polar Ocean = 2
% Reef = 3
% Tiaga = 4
% Kelp Forest = 5
% Deep Open Ocean = 6

enum=3;
r=FitFact(enum);
Totals=MobChar(enum);
T=Totals;
Fval=r.*T;
Final_Value = Fval'/max(Fval);
fprintf('\n')
fprintf('Final Value: %0.5f\n',Final_Value)
fprintf('\n')
R=EnviCorrCo(enum);
```

Figure 41: Matlab Script File "All Code Test"

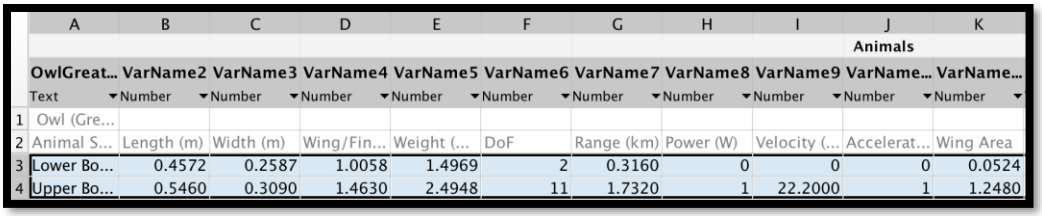
It can be seen that the script calls results from other function files and evaluate them to total the final scoring needed for the final output. The variable “enum”, depicted above, describes what working environment the user will be implemented. This variable is accompanied by a legend describing each environment by number to help clarify the process.

5.2.2 Outputs

The outputs of the script file are the final scores to the animal specification mobility analysis. It is felt that the user does not need to see the inner workings of the various function files as the user will not be manipulating it, unless the user is inputting additional animal and/or environmental information.

5.3 Data Sets

The data sets used within the Matlab functions are informational sources and include information on animal and environmental specifications. An example of an animal dataset is displayed in Figure 42, below.



	A	B	C	D	E	F	G	H	I	J	K
										Animals	
	OwlGreat...	**VarName2**	**VarName3**	**VarName4**	**VarName5**	**VarName6**	**VarName7**	**VarName8**	**VarName9**	**VarName...**	**VarName...**
	Text	Number	Number	Number	Number	Number	Number	Number	Number	Number	Number
1	Owl (Gre...										
2	Animal S...	Length (m)	Width (m)	Wing/Fin...	Weight (...	DoF	Range (km)	Power (W)	Velocity (...	Accelerat...	Wing Area
3	Lower Bo...	0.4572	0.2587	1.0058	1.4969	2	0.3160	0	0	0	0.0524
4	Upper Bo...	0.5460	0.3090	1.4630	2.4948	11	1.7320	1	22.2000	1	1.2480

Figure 42: Example of animal data set sheet

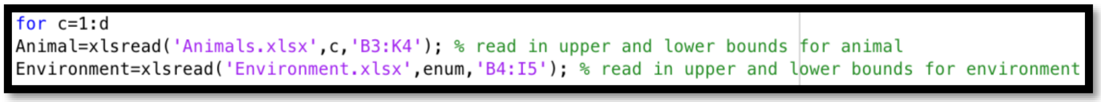
Each dataset contains lower and upper bounds for each quantified animal or environmental specification. In some cases there was not much variation between the lower and upper bounds due to low variability within the specified measurement itself. This itself is not an issue, however in the cases where know the variability was documented, an assumption of variability was made. The functions or written in such a way that some sort of variability was necessary, and in fact to user would receive an error message if know variability was taken into account. For this project it was standard practice to determine the variability of no larger than one unit as to not enter too much undesirable variation.

5.3.1 Layout

The animal and environmental specification information was stored in respective Microsoft Excel files. Within each file the user can input specification boundary information on animal or environmental specific sheets. This allows for the data to be stored in an uncluttered way, as well as make it easier for a user to add more animals or environments to the database.

5.3.2 Reading Data

Within the Matlab code, the animal and environmental specification data was read by using the function “xlsread”, which was incorporated in both the fitness for score function file and mobility characteristics function file. Example of this implementation is depicted in Figure 43.



```
for c=1:d
Animal=xlsread('Animals.xlsx',c,'B3:K4'); % read in upper and lower bounds for animal
Environment=xlsread('Environment.xlsx',enum,'B4:I5'); % read in upper and lower bounds for environment
```

Figure 43: Matlab Code Example: Reading data sheet information

The animal and environmental specification values were read within a for loop, we’re the variable c represent the number of animals being considered and in turn which animal sheet was being read. The environmental sheets we’re determined based on the variable enum, which representing the working environment that the user would choose in the all code script file. Within the function files, the bounds being read for the animal and environmental specifications can be modified based on how many specifications the user may have. This allows for ease-of-use when modifying the specifications sheets to allow for more for less specification values.

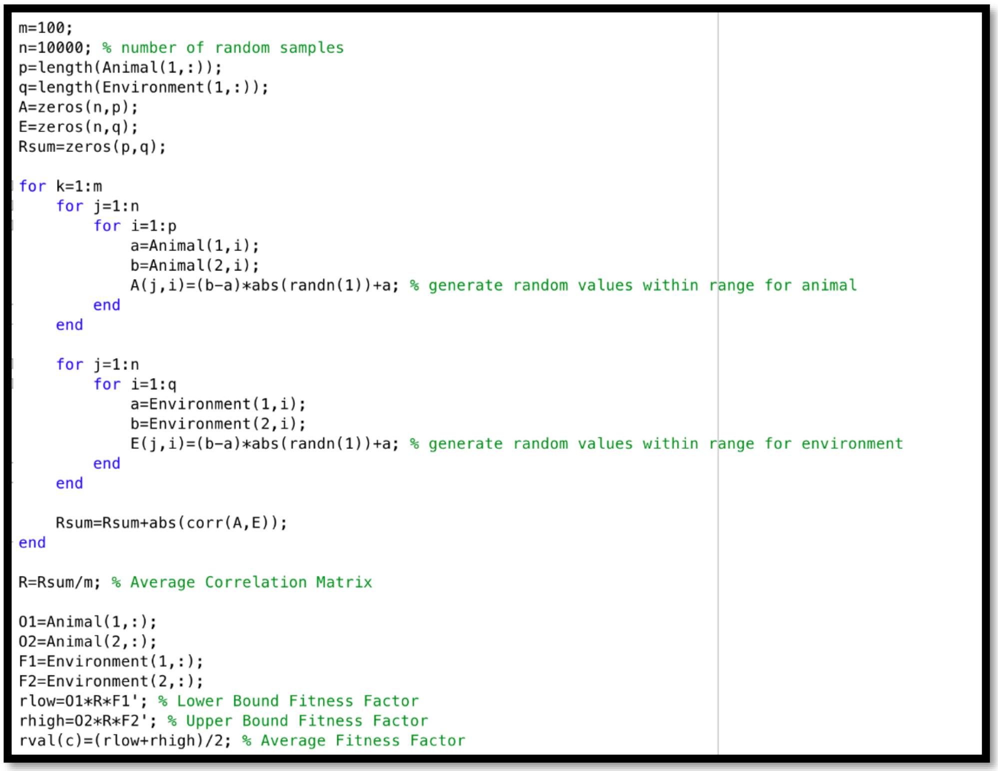
5.4 Fit Fact

For this project, the FitFact function included operations to produce a specified number of random samples animal and environmental specifications, as well as predict an animal fitness score based on a specified working environment. The following sections will detail these operations and explain how they were done.

5.4.1 Overall Function

For this project the fitness score of an animal was developed to determine how well an animal functions within environment, and was based on specification data for both the animal and the working environment. The fitness score, described in chapters 1 and 2, are depicted in Figures 3 and 6.

The fitness score matrix operations describes how an animal can be described by a value and how that value is created using the correlation between the specified animal in the working environment. This operation was built within the FitFact function file using a for loop to Help populate the animal environmental specification sheets, using the upper and lower bounds that were previously described. Figure 44 displays this operation in the Matlab format.



```
m=100;
n=10000; % number of random samples
p=length(Animal(1,:));
q=length(Environment(1,:));
A=zeros(n,p);
E=zeros(n,q);
Rsum=zeros(p,q);

for k=1:m
    for j=1:n
        for i=1:p
            a=Animal(1,i);
            b=Animal(2,i);
            A(j,i)=(b-a)*abs(randn(1))+a; % generate random values within range for animal
        end
    end

    for j=1:n
        for i=1:q
            a=Environment(1,i);
            b=Environment(2,i);
            E(j,i)=(b-a)*abs(randn(1))+a; % generate random values within range for environment
        end
    end

    Rsum=Rsum+abs(corr(A,E));
end

R=Rsum/m; % Average Correlation Matrix

O1=Animal(1,:);
O2=Animal(2,:);
F1=Environment(1,:);
F2=Environment(2,:);
rlow=O1*R*F1'; % Lower Bound Fitness Factor
rhigh=O2*R*F2'; % Upper Bound Fitness Factor
rval(c)=(rlow+rhigh)/2; % Average Fitness Factor
```

Figure 44: Matlab FitFact function used to determine an animal's fitness score

5.4.2 Creating Samples

The random samples generated to determine the fitness score were done so using the “randn” function within Matlab. This function helps create random numbers that are normally distributed [162]. Using this function was validated through the assumption that animal measurements tend to follow a normally distributed trend [163]. Figure 44, above, shows the used of the random number function and how it was used to create one hundred thousand samples between the dictated boundary conditions.

5.4.3 Outputs

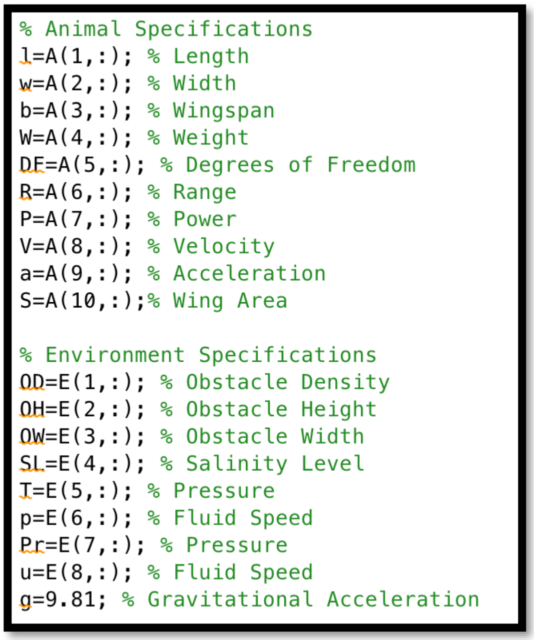
The FitFact function uses the correlated values to determine a set number of fitness scores, in uses the lower and upper bound fitness factors to determine average fitness score based on all the sample specifications for each individual animal and each sample set of specification values for the chosen working environment. Depending on user preference, the function may or may not output the determined fitness scores. This would only be necessary if the user is interested in the predicted score alone without any information in regards to animal mobility.

5.5 Mob Char

The animal mobility characteristics are determined within the function file MobChar. Within this function the various mobility characteristics are determined based on the animal in environmental specification values provided by the user or the animal and environmental database. The MobChar function evaluate each mobility characteristic calculated and uses these characteristics to complete a Monte Carlo Analysis for each mobility characteristic. The details of this process are explained in the following below.

5.5.1 Overall Function

Mobility characteristics function implements the normally distributed random samples to calculate the functions describing the six mobility characteristics: hover, glide, dive, soar, and flapping/swimming movement. Figure 45 depicts how the animal and environmental specifications were created and used in the mobility characteristics function file.



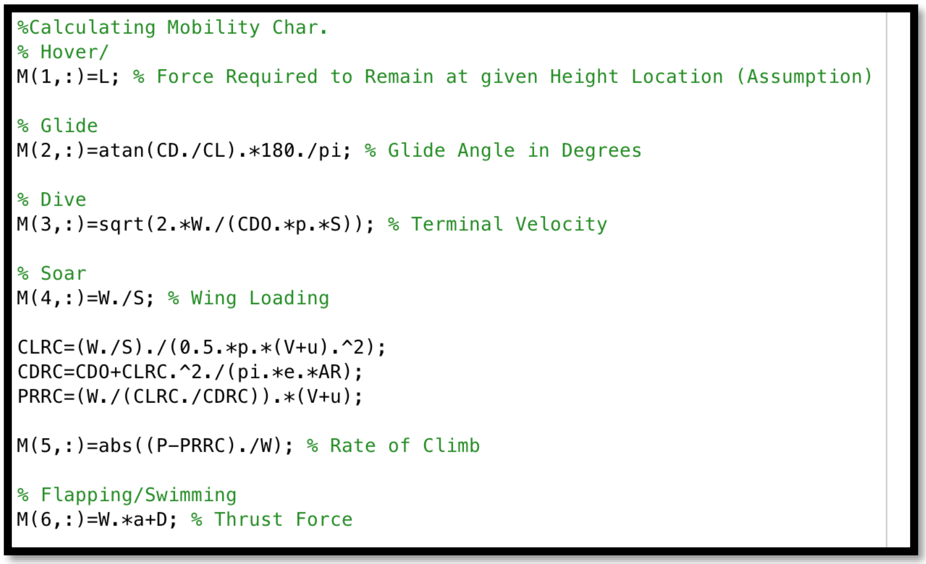
```
% Animal Specifications
l=A(1,:); % Length
w=A(2,:); % Width
b=A(3,:); % Wingspan
W=A(4,:); % Weight
DF=A(5,:); % Degrees of Freedom
R=A(6,:); % Range
P=A(7,:); % Power
V=A(8,:); % Velocity
a=A(9,:); % Acceleration
S=A(10,:);% Wing Area

% Environment Specifications
OD=E(1,:); % Obstacle Density
OH=E(2,:); % Obstacle Height
OW=E(3,:); % Obstacle Width
SL=E(4,:); % Salinity Level
T=E(5,:); % Pressure
p=E(6,:); % Fluid Speed
Pr=E(7,:); % Pressure
u=E(8,:); % Fluid Speed
g=9.81; % Gravitational Acceleration
```

Figure 45: Matlab Code for specification values used in various mobility characturistics

The animal and environmental specifications or created using the perspective cell locations within the animal in environmental datasheets. This will allow for ease of use when extracting a specific animal specification in using it determining mobility characteristic.

5.5.2 Creating and Storing Mobility Characteristics

The mobility characteristics I determined through calculations and based on the given specification values for the animal and the working environment. The following figure, Figure 46, shows the animal mobility characteristic calculations for this project.



```
%Calculating Mobility Char.
% Hover/
M(1,:)=L; % Force Required to Remain at given Height Location (Assumption)

% Glide
M(2,:)=atan(CD./CL).*180./pi; % Glide Angle in Degrees

% Dive
M(3,:)=sqrt(2.*W./(CDO.*p.*S)); % Terminal Velocity

% Soar
M(4,:)=W./S; % Wing Loading

CLRC=(W./S)./(0.5.*p.*(V+u).^2);
CDRC=CDO+CLRC.^2./(pi.*e.*AR);
PRRC=(W./(CLRC./CDRC)).*(V+u);

M(5,:)=abs((P-PRRC)./W); % Rate of Climb

% Flapping/Swimming
M(6,:)=W.*a+D; % Thrust Force
```

Figure 46: Mobility characteristic equations in Matlab

The figure above to pics several variables that are not among the specification values found in the database. In particular, the coefficient of lift and coefficient drag variables are not considered measurable specification. These values were randomly simulated based on assumptions in regards to capability, due to a lack of available data concerning the lift and drag coefficients of various animals. Lift and drag coefficient as well as the Oswald efficiency factor or determined based on low rounds numbers as well as randomness as provided in the code. The coefficient of lift was the only variable that was chosen rather than selected randomly, and select to be a value of 1.5. the other variables included randomness as they were built upon other variables in which random this could be applied.

5.5.3 Monte Carlo Simulation

The Monte Carlo simulation implemented in this project is based around the mobility characteristics calculations and the random simulated sampling of the specification values.

For the Monte Carlo analysis, mobility characteristics were calculated based on one hundred thousand samples of simulated data and used to create histograms, using the “histfit” function, of that data and a fit curve based on a 95% confidence interval. The fit curves overlay the histograms, and may be visually inspected to determine whether the data best fits that of a curve with a normal, log normal, exponential, or uniform distribution. A sample of the Monte Carlo simulation output for one animal is depicted in Figure 47, below.

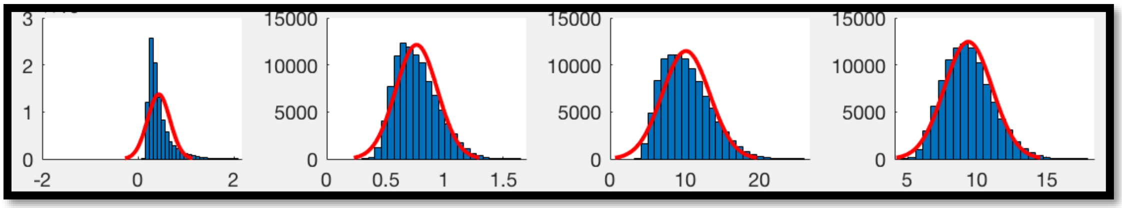


Figure 47: Mobility characteristic histogram example

Figure 47 displays the first four mobility characteristics that were calculated for a random animal. To present the data any readable manner the histograms were limited to 25 bins. You can be seen that while the distribution on the right almost aligns with a normal fit curve, the histogram on the left depicts in more exponential curve type and the curves in the center clearly depict lognormal curved types. Outputs of the Monte Carlo simulation include maximum and minimum values for each analysis as well as the mean value. These values were obtained using the “fitdist” function within Matlab.

5.5.4 Ranking Setup

From the Monte Carlo simulation, maximum and minimum values were used to determine a ranking order based on the mobility characteristics. The ranking system is set up to either ranked from highest to lowest or vice versa based on user desire. The ranking structure within Matlab is depicted in Figure 48, below.

```
Totals=0;
fprintf('\n')
for i=1:6
    fprintf('\n')
    if i==2
            fprintf('Ranking for ')
            disp(Mnames(i,:))
            [~,An]=sort(avg(:,i))
            for j=1:length(An)
                Rank=names(An(j),:)
                disp(Rank)
            end
    else
            fprintf('Ranking for ')
            disp(Mnames(i,:))
            [~,An]=sort(-avg(:,i))
            for j=1:length(An)
                Rank=names(An(j),:)
                disp(Rank)
            end
    end
    Totals=Totals+An;
end

fprintf('\n')
fprintf('Total Ranking Sums\n')
for i=1:k
    disp(names(i,:))
    fprintf(' %0.0f\n',Totals(i))
end
```

Figure 48: Matlab ranking structure

Within the ranking process, each calculated mobility characteristic for an animal was evaluated based on user desire and rank against other animal’s mobility characteristics. The ranking values where than given in order from one to n, n being the total number of animals used in the comparison. For example, it’s eight animals are compared to one another, then the highest rank that in animal could achieve would be eight and the lowest would be one.

The ranking values we’re totaled, and each total was multiplied by the respective fitness score for the animal represented. These final values depict the final scores for the ranking system.

5.6 Code Conclusions

While the functions and analysis perform as designed, there are a couple ways in which the code could be improved to run in a more timely manner and to increase clarity. In regards to time, the code could be simplified, as some parts are duplicated between function files. This adds unnecessary calculations and increases the run time of the program. Another concern maybe variable accessibility. The code is designed to limit the user interaction with the function files to reduce the risk of errors. However, some variables may be further required and therefore will need more accessibility between them and the user. This may involve how certain variables are stored or could involve user interaction at different points throughout the process. This would be and ideal stage for a GUI to be implemented, as it will guide the user by means of an uncluttered interface.

6. Conclusion

This chapter will discuss the overall Animal Specification Mobility Analysis (ASMA) methodology and the results in two parts. The first section of this chapter will discuss concluding remarks in regards to methodology and overall results obtained through the proposed process. The structure of the methodology, in terms of the research gaps addressed, will be reviewed and the process in which we addressed the gaps will be reassessed. This section also includes information on the usability of the proposed methodology in terms of the current user interface and how a user may manipulate the program to better suit the needs of a given mission. The second section of the chapter will review methodology results in terms of the results obtained through addressing each of the research gaps. These results will be displayed in terms the overall process and not specific to any particular mission.

6.1 Methodology

The ASMA methodology developed for this project address various research gaps by implementing automation within the bio-inspired design process, quantitative descriptors of performance for biological terminology, and the implementation of a data schema used to represent animals and environments. The ASMA methodology maybe visually represented in the following figure, Figure 49.

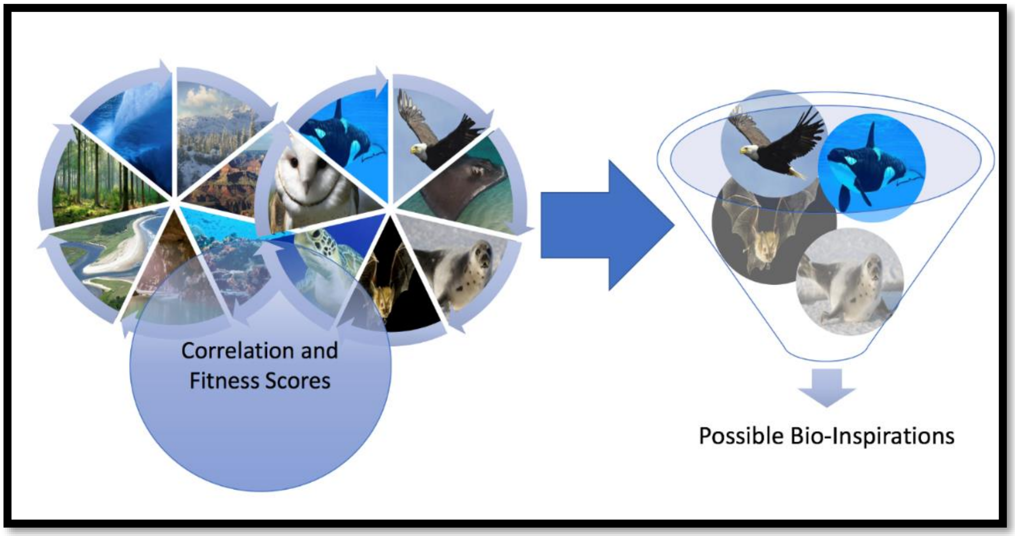
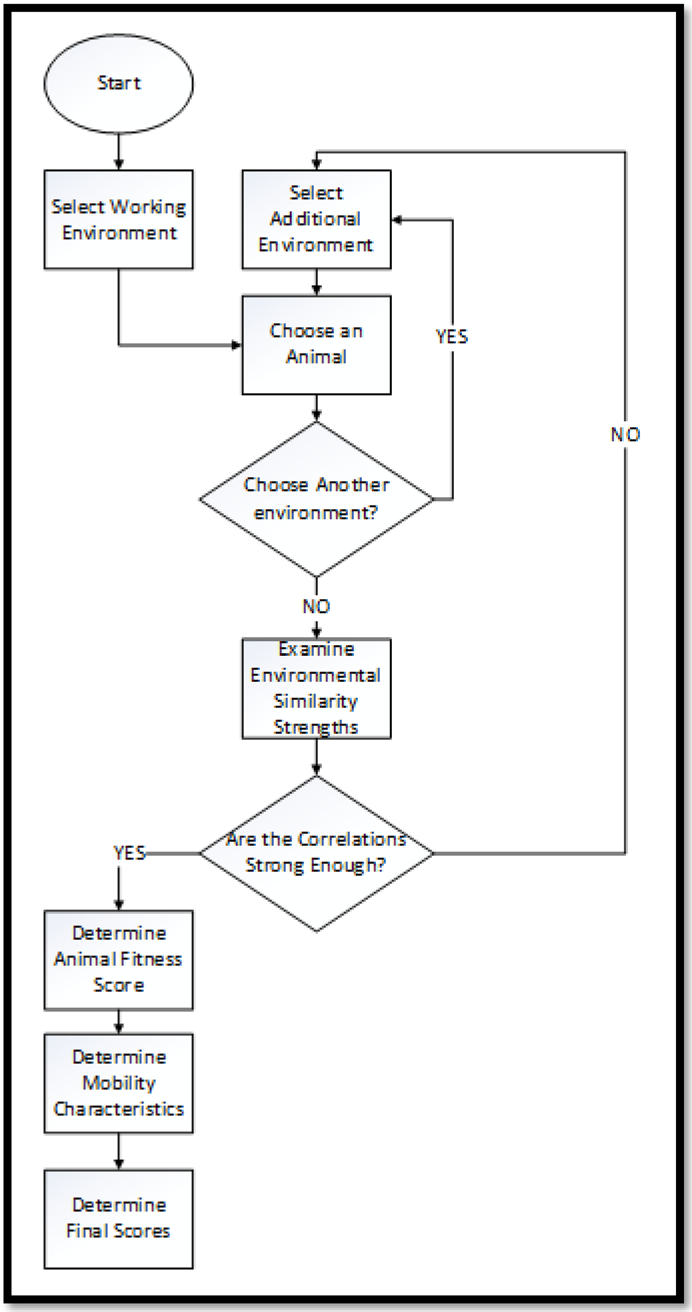


Figure 49: ASMA Methodology Imagery [1]–[14]

Figure 49 portrays the overall methodology by representing the user's choice of a working environment as an environment wheel, and the various choices of animal prospects in an animal wheel display. The combinations of these data sets results in the correlation matrix and the animal fitness scores. This information is then transferred to the ranking system, as each animal is subjected to a filtering process composed of steps to determine various mobility characteristics. The results from the mobility characteristics are ranked and result in a quantitative and weighted score used to determine the best possible bio-inspiration.

6.2 Process Flow Chart

The ASMA methodology is based on a user designing for a mission specific environment and can help determine a viable bio inspiration to be used for a vehicle design that must function within the mission environment. A flow chart of the ASMA process is displayed again below in Figure 50.



As depicted in the figure above, the ASMA process begins by selecting a working environment. The working environment is the environment in which the mission will take place and will be defined by the mission profile, therefore being information that the user will have access to. The user will then choose an animal that inhabitants the working environment. At this point the user has the option to choose another environment, followed by choosing another animal to compare with the original animal.

When the user satisfied with the animal selection (or selections), the user may explore the strength of the similarity between each of the chosen environment. If the similarity strength is not strong enough, based on user interpretation, the user may go back and select a new set of environments and corresponding animals. If the similarity correlations are strong enough, the user may move forward in determining respective animal fitness scores, mobility characteristics, and final scores. Scores may then be interpreted by the user, who is then free to choose to move forward with a selected bio inspiration.

6.3 Results

This section discusses the results obtained through implementing the ASMA program into the BID process, in terms of both research gaps and research approach questions.

6.3.1 Research Gaps

The gaps found within bio inspired design research were based on lacks in information, processes, automation, and common terminology between the fields of biology and mechanical engineering. These gaps are reiterated below, and accompanied by statements describing the needs that existed due to the research gaps and how this research has met these gaps.

BID gap 1: ***A lack of automation in the bio-inspired design process.***

Automation within the BID process is a need that must be filled in order to achieve a user friendly and modernized solver that may direct a user, through a focused search strategy, to an ideal inspirational source. This research has addressed this gap by implementing an automated process, built upon a database of animal and environmental specification.

BID gap 2: ***A missing standard for determining a "better" inspirational source from biology.***

The standard for a "better" inspirational source is not well defined within the BID process. Therefore, there is not a standardized method that exists that may tell a designer what inspirational source is more ideal for a given mission environment. A need exists for a methodology that allows innovators to design based on measureable biological characteristics and calculated functionality estimations. This research has addressed this need by representing the functionality of an animal within an environment, via a fitness score, which is based on a specific mission profile.

BID gap 3: ***No mechanical ranking system based on biology and the natural world exists***.

This gap identified the need for a ranking system that may direct a designer to an ideal inspirational source, and by doing so bridge the gap between biology and mechanical engineering though the use of measureable and rank-able characteristics. This research addresses this gap I implementing a ranking system based on animal mobility characteristics, which describe the movement of an animal and are based on biological terms.

BID gap 4: ***A lack of focus on capability and mobility linking the bio and mechanical world exists***.

The final research gap addressed in this work focused on a need to implement measurable biological characteristics to a design process in terms of both bio inspiration and mechanical engineering. This need was addressed by implementing a ranking system that focused on the mobility of an animal in the importance of its respective capability within it working environment.

While the research gaps addressed in this project gave way to process implementations for a more refine BID method, the gaps were addressed in parallel with the research approach questions.

6.3.2 Research/Approach Questions

The research questions for this project, unlike the research gaps, were goals set in order to create a methodology to design vehicles with aerodynamic and/or hydrodynamic capabilities suitable to give an operating environment. The methodology created in this project focused on the functionality of a vehicle design based on a bio inspiration, and ways to numerically represent the mobility of the specified animal. The overarching research question answered in this work is as follows:

> *"Can biological information be categorized by performance measures to support the design and functional optimization of vehicles that operate in complex environments?"*

As previously stated this question was broken into four research questions, which identified four goals that would need to be achieved to answer the overarching research question. These questions are reiterated below, accompanied by statements that describe how each of the research questions were answered within this project.

Research Question 1: Can we achieve correlation between environmental specifications and animal specifications?

This question was derived to determine what makes an animal best suited to function within environment. The ASMA program implements a database of measureable specification values, for both animals and environments, and uses these values to determine an animal to environment correlation. The correlation itself is a comparison of each animal specification to each environmental specification and the results of the correlation maybe displayed in a matrix, where each cell represents a correlation strength between zero and one.

Research Question 2: Can we achieve a fitness score to represent animals that function within a specified environment?

The functionality of an animal within environment is key to this methodology as it represents how well an animal may function within an environment as well as help weight the importance and strength of each respective summed animal mobility characteristic. For this project, the fitness scores were achieved using the combined animal and environmental specifications as well as the correlation matrix describing the functionality of an animal with the environment.

Research Question 3: Can we produce animal or environmental similarity matrices to compare specification values of animals or environments?

Within this research similarity matrices where used to compare environments based on environmental specification values. The strength of the environmental similarities where used to determine whether or not another environment may be a viable source for another possible biological inspiration. Improper scale for environmental similarity has not been justified at this point, however the similarity strengths maybe used based on user discretion and with the understanding that the higher similarity values will represent environment that may prove to be worth investigating.

Research Question 4: Can we quantify animal mobility functions as either binary effects or a set of numerical representations?

For this research, the animal mobility functions were based off of free body diagrams and corresponding equations used to describe the various biological mobility terms. Implementing the animal mobility functions proved more beneficial than originally assumed, because the original idea was just to describe animal motion using physical equations. However, the end result utilized biological terms and related these terms to the physical equations being used. This allowed for these biological terms to be described in an engineering fashion, ultimately helping bridge the gap between biology and mechanical engineering so that these biological terms maybe better understood between all parties involved within the BID process.

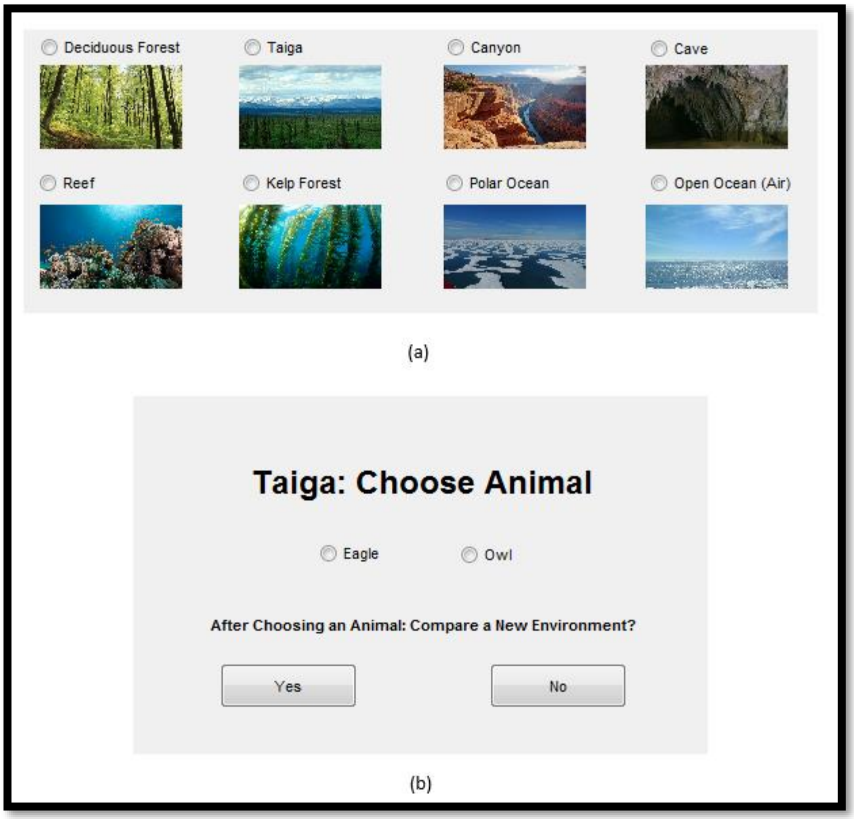
From the results based on the gaps found within literature and the research approach questions, it can be seen that this research project has achieved all the goals set forth by the lacks in the current studies and has answered all the questions derived from the overarching research question for this project. Therefore it can be assumed that it is possible to categorize biological parameters by performance measures to support the design and functional optimization of vehicles that operate in complex environments.

7. Future Work

This section will detail future work that maybe desired by designers working on BID projects. The work discussed here involves additions and/or modifications that may be used update the proposed methodology provided in this work. Many examples shown in this section are predicted to further design processes involving bio-inspirations.

7.1 GUI

It is important to have a graphical user interface (GUI) that implements ease-of-use and simplicity to a designer, especially when so many conditions and specifications are being considered. A GUI interface is currently being constructed for this project, yet still lacks simplicity in its creation and therefore adds additional and wasted time to the design process. The GUI currently in construction displays a combination of words and imagery to help the user select various design choices. An example of two GUI windows are presented below in figure 51.



Taiga: Choose Animal

After Choosing an Animal: Compare a New Environment?

Figure 50: ASMA GUI Example

Figure 51 (a) depicts a window in which environments are described both texturally and graphically. The user has the option to choose which environment they would like to use for the working environment, in which a specific mission must be completed. Once an environment is chosen, the user then has the option to pick an animal within that environment to begin making comparisons with, as depicted in Figure 51 (b). At this point, the designer would again have the chance to pick a new environment and a new animal, and so on, until the user feels they have chosen the needed animals to make comparisons with.

A GUI implements clarity and ease of use to a user by illuminating the users interactions with the script files. This also eliminates the technical skill needed to use the raw code and creates a broader user base. A GUI may also be found more aesthetically pleasing, and therefore encourage users to engage more with a program.

7.2 More animals

While this project focus on aerodynamic and hydrodynamic animals and their corresponding mobility characteristics, it would be beneficial to improve upon this methodology by including the more animals, diverse in nature. Animals may include terrestrial animals such as large cats, bears, primates, or any other type of mammal. Various insects should also be explored as well as different types of birds, fish and reptiles. This methodology could prove limitless in what may be explored or implemented in terms of biological inspired design. Acquiring such a large range of animals for this process would also require an update in terms of the animal specifications. The current specifications are focused towards animals with aerodynamic and/or hydrodynamic abilities, due to the needs for the mobility characteristic calculations, while other specification information maybe needed for other types of mobility characteristic analysis. This may include information pertaining to coefficient of friction for the animals skin, turning radius, and deceleration.

7.3 More Environments

For this project, information was obtained to maximize the output of the result, including the number of complex environments. Thus far we have specification information to complete six environments and partial specification values for a few other environments.

Based on this small number of working environments to choose from, it is believe that the environment data sheet should be expanded so that other animals may be introduced to the proposed BID process. With the small number of environments, a user cannot fully take advantage of the design system presented in this work. Complex environments should be further explored and added to the environment data as to broaden the spectrum of possibilities that a designer may achieve through BID.

7.4 User created Environments

While implementing more environments to the proposed BID system would be beneficial, there might be a couple of different ways in which to begin exploring other environments. First, this project should explore the idea of user created environments. This idea promotes users to create environments based on qualitative environmental descriptors and have these descriptions help indicate related specification values that may be found in such environments that the user may describe.

7.5 Extraterrestrial Environments

Second, due to the interest space studies and exploration, it is believed that it would be beneficial to develop extraterrestrial environments to help guide designers towards a solution using a BID approach. As technology develops, designers can obtain more specification information in regards to extraterrestrial working environments, which may lead to new and perhaps unconventional designs that function better than the current state rovers and robotics used to function on other planetary surfaces.

7.6 Specifications and Fitness Scores

Future work should include updating the specification values for this project. This includes refining assumptions and adding new specifications to increase the animal datasets, which will add more robustness to the data. By creating a more robust data set, designers will have a more robust fitness score as the first directly affects the latter.

7.7 Mobility Characteristics

As with the specification values, the mobility characteristics and corresponding analysis should be updated and enhanced by adding more calculations to describe the possible movement of an animal. There are a couple benefits to such additions. First, as with the specification values, the mobility characteristics would become more robust with more data and more equations to describe such motion. The more robust the system becomes, the more reliable it will be to a designer. Second, if the mobility characteristics and the specifications used to mathematically describe them can be improved, then the proposed method may also be updated as a whole to include other mobility types such as walking, running, jumping, and various types of swimming. Knowing more about possible motion types will help drive designers to look for more types of animals and their related environments.

7.8 A methodology to Design for actions

The methodology presented in this work focuses on the mobility characteristics that maybe attained by potential bio-inspiration source. However this work does not look into actions or tasks that maybe needed to complete a mission. It is believed that in methodology that focuses on both a design to function in a complex environment and they design for action required it Is beneficial in meeting then needs for a specific mission. Adding in a design methodology for action would detail designs in a greater capacity and could be complemented by common engineering tools, such as a House of Quality, in such a way that the designer could now directly address customer requirements in terms of accomplishing a specific task.

7.9 Design Resiliency

This dissertation presents a methodology to help guide designers produce viable bio-inspirational mechanical vehicles that may function within complex environments. Further work may be applied to this research in terms of resiliency within a biological inspired design. This research may benefit from a cost risk analysis of a potential bio-inspired system, [177], and even a focus on uncertainty, as displayed in [178] and [179], as the Monte Carlo analysis does involve a level of uncertainty related to the simulated specification values within the ASMA methodology. These design methods may be presented during the early stages of the ASMA methodology to ensure a more accurate design for these complex designs [180].

8. Bibliography

[1] K. Fu, D. Moreno, M. Yang, and K. L. Wood, “Bio-inspired design: an overview investigating open questions from the broader field of design-by-analogy,” *Journal of Mechanical Design*, vol. 136, no. 11, p. 111102, 2014.

[2] M. Helms, S. S. Vattam, and A. K. Goel, “Biologically inspired design: process and products,” *Design Studies*, vol. 30, no. 5, pp. 606–622, 2009.

[3] M. S. Aziz, “Biomimicry as an approach for bio-inspired structure with the aid of computation,” *Alexandria Engineering Journal*, vol. 55, no. 1, pp. 707–714, 2016.

[4] M. W. Glier, D. A. McAdams, and J. S. Linsey, “Concepts in biomimetic design: methods and tools to incorporate into a biomimetic design course,” in *ASME 2011 international design engineering technical conferences and computers and information in engineering conference*, 2011, pp. 655–660.

[5] Y.-C. Chou, H. Cao, and H. H. Cheng, “A bio-inspired mobile agent-based integrated system for flexible autonomic job shop scheduling,” *Journal of Manufacturing Systems*, vol. 4, no. 32, pp. 752–763, 2013.

[6] A. Shoemaker and A. Leonessa, “Bio-inspired nonholonomic tracking control,” in *ASME 2013 Dynamic Systems and Control Conference*, 2013, p. V001T07A004–V001T07A004.

[7] J. J. Son, C. Raulf, H. Cheong, and L. H. Shu, “Exploring the Collective Categorization of Biological Information for Biomimetic Design,” in *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2012, pp. 393–401.

[8] Y. Hou and J. I. Linhong, “Gene Transcription and Translation in Design,” in *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2015, p. V007T06A001–V007T06A001.

[9] F. Pati, D.-H. Ha, J. Jang, H. H. Han, J.-W. Rhie, and D.-W. Cho, “Biomimetic 3D tissue printing for soft tissue regeneration,” *Biomaterials*, vol. 62, pp. 164–175, 2015.

[10] S. Mohanty *et al.*, “Fabrication of scalable and structured tissue engineering scaffolds using water dissolvable sacrificial 3D printed moulds,” *Materials science and engineering: C*, vol. 55, pp. 569–578, 2015.

[11] C.-T. Kao, C.-C. Lin, Y.-W. Chen, C.-H. Yeh, H.-Y. Fang, and M.-Y. Shie, “Poly (dopamine) coating of 3D printed poly (lactic acid) scaffolds for bone tissue engineering,” *Materials Science and Engineering: C*, vol. 56, pp. 165–173, 2015.

[12] A. Borhani and N. Kalantar, "THE EMERGENCE OF A NEW MATERIAL CULTURE: FORGING UNPRECEDENTED ALLIANCES BETWEEN DESIGN AND ENGINEERING," in *DS 83: Proceedings of the 18th International Conference on Engineering and Product Design Education (E&PDE16), Design Education: Collaboration and Cross-Disciplinarity, Aalborg, Denmark, 8th-9th September 2016*, 2016.

[13] P. Egan, S. J. Ferguson, and K. Shea, "Design and 3D printing of hierarchical tissue engineering scaffolds based on mechanics and biology perspectives," in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, p. V007T06A002–V007T06A002.

[14] P. A. Levett, F. P. Melchels, K. Schrobback, D. W. Hutmacher, J. Malda, and T. J. Klein, "A biomimetic extracellular matrix for cartilage tissue engineering centered on photocurable gelatin, hyaluronic acid and chondroitin sulfate," *Acta biomaterialia*, vol. 10, no. 1, pp. 214–223, 2014.

[15] P. Datta, S. Dhara, and J. Chatterjee, "Hydrogels and electrospun nanofibrous scaffolds of N-methylene phosphonic chitosan as bioinspired osteoconductive materials for bone grafting," *Carbohydrate polymers*, vol. 87, no. 2, pp. 1354–1362, 2012.

[16] C. Cheng *et al.*, "Biopolymer functionalized reduced graphene oxide with enhanced biocompatibility via mussel inspired coatings/anchors," *Journal of Materials Chemistry B*, vol. 1, no. 3, pp. 265–275, 2013.

[17] M. Albertini *et al.*, "Advances in surfaces and osseointegration in implantology. Biomimetic surfaces," *Medicina oral, patologia oral y cirugia bucal*, vol. 20, no. 3, p. e316, 2015.

[18] S. W. Lee, K. A. Landers, and H.-S. Park, "Biomimetic hand exotendon device (BiomHED) for functional hand rehabilitation in stroke," in *Rehabilitation Robotics (ICORR), 2013 IEEE International Conference on*, 2013, pp. 1–4.

[19] M. Hosseinipour and M. Elahinia, "Bioinspired Design of IntraVAD Assistive Device for Congestive Heart Failure Patients Using Ionic Polymer Metal Composites and Shape Memory Alloys," in *ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2013, p. V002T06A025–V002T06A025.

[20] B. Lo, S. Thiemjarus, A. Panousopoulou, and G.-Z. Yang, "Bioinspired design for body sensor networks [life sciences]," *IEEE Signal Processing Magazine*, vol. 30, no. 1, pp. 165–170, 2013.

[21] M.-A. Nguyen and S. A. Sarles, "Micro-Encapsulation and Tuning of Biomolecular Unit Cell Networks," in *ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2014, p. V002T06A012–V002T06A012.

[22] E. C. Freeman, M. K. Philen, and D. J. Leo, "Principles of Biomolecular Network Design," in *ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2013, p. V002T06A009–V002T06A009.

[23] C. Lavilla, A. M. de Ilarduya, A. Alla, M. de G. García-Martín, J. A. Galbis, and S. Muñoz-Guerra, "Bio-based aromatic polyesters from a novel bicyclic diol derived from d-mannitol," *Macromolecules*, vol. 45, no. 20, pp. 8257–8266, 2012.

[24] R. V. Ottenbacher, D. G. Samsonenko, E. P. Talsi, and K. P. Bryliakov, "Highly enantioselective bioinspired epoxidation of electron-deficient olefins with H2O2 on aminopyridine Mn catalysts," *ACS Catalysis*, vol. 4, no. 5, pp. 1599–1606, 2014.

[25] S. Yuan *et al.*, "Flexible Zirconium Metal-Organic Frameworks as Bioinspired Switchable Catalysts," *Angewandte Chemie International Edition*, vol. 55, no. 36, pp. 10776–10780, 2016.

[26] G. M. Whitesides, "Bioinspiration: something for everyone," *Interface focus*, vol. 5, no. 4, p. 20150031, 2015.

[27] J. K. Nagel, "Design of a Biologically-Inspired Chemical Sensor," in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, p. V004T08A049–V004T08A049.

[28] A. Goel *et al.*, "Using Watson for Supporting Design Creativity," in *DS86: Proceedings of The Fourth International Conference on Design Creativity, Georgia Institute of Technology, Atlanta, GA, USA*, 2016.

[29] D. Vandevenne, P.-A. Verhaegen, S. Dewulf, and J. R. Duflou, "Automatically populating the Biomimicry Taxonomy for scalable systematic biologically-inspired design," in *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2012, pp. 383–391.

[30] J. Tsenn, J. S. Linsey, and D. A. McAdams, "Bioinspired materials design: An assessment of methods to improve a text mining algorithm for identifying biological material structural design principles," in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, p. V007T06A001–V007T06A001.

[31] J. Tsenn, J. S. Linsey, and D. A. McAdams, "Development of a search tool to identify structural design principles for bioinspired materials design," in *ASME 2014*

International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2014, p. V007T07A001–V007T07A001.

[32] D. Vandevenne, P.-A. Verhaegen, S. Dewulf, and J. R. Duflou, “Product and organism aspects for scalable systematic biologically-inspired design,” *Procedia engineering*, vol. 131, pp. 784–791, 2015.

[33] H. Cheong and L. H. Shu, “Automatic extraction of causally related functions from natural-language text for biomimetic design,” in *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2012, pp. 373–382.

[34] M. J. Hancock, K. Sekeroglu, and M. C. Demirel, “Bioinspired directional surfaces for adhesion, wetting, and transport,” *Advanced functional materials*, vol. 22, no. 11, pp. 2223–2234, 2012.

[35] Z. Rong *et al.*, “Bio-Inspired Hierarchical Polymer Fiber–Carbon Nanotube Adhesives,” *Advanced Materials*, vol. 26, no. 9, pp. 1456–1461, 2014.

[36] M. Zhou, N. Pesika, H. Zeng, Y. Tian, and J. Israelachvili, “Recent advances in gecko adhesion and friction mechanisms and development of gecko-inspired dry adhesive surfaces,” *Friction*, vol. 1, no. 2, pp. 114–129, 2013.

[37] Y.-Q. Li, T. Yu, T.-Y. Yang, L.-X. Zheng, and K. Liao, “Bio-inspired nacre-like composite films based on graphene with superior mechanical, electrical, and biocompatible properties,” *Advanced Materials*, vol. 24, no. 25, pp. 3426–3431, 2012.

[38] A. Prasad, K. Mahato, P. Chandra, A. Srivastava, S. N. Joshi, and P. K. Maurya, “Bioinspired Composite Materials: Applications in Diagnostics and Therapeutics,” *Journal of Molecular and Engineering Materials*, vol. 4, no. 01, p. 1640004, 2016.

[39] A. R. Studart, “Towards high-performance bioinspired composites,” *Advanced Materials*, vol. 24, no. 37, pp. 5024–5044, 2012.

[40] A. Saito, “Material design and structural color inspired by biomimetic approach,” *Science and technology of advanced materials*, vol. 12, no. 6, p. 064709, 2012.

[41] J. Zhang, J. Wang, and H. Tian, “Taking orders from light: progress in photochromic bio-materials,” *Materials Horizons*, vol. 1, no. 2, pp. 169–184, 2014.

[42] C. T. Koh, C. Y. Low, and Y. bin Yusof, “Structure-property relationship of bio-inspired fibrous materials,” *Procedia Computer Science*, vol. 76, pp. 411–416, 2015.

[43] M. Mirkhalaf, A. K. Dastjerdi, and F. Barthelat, “Overcoming the brittleness of glass through bio-inspiration and micro-architecture,” *Nature communications*, vol. 5, p. 3166, 2014.

[44] X. Yang *et al.*, “Bioinspired fabrication of free-standing conducting films with hierarchical surface wrinkling patterns,” *ACS nano*, vol. 10, no. 3, pp. 3801–3808, 2016.

[45] O. Im, J. Li, M. Wang, L. G. Zhang, and M. Keidar, “Biomimetic three-dimensional nanocrystalline hydroxyapatite and magnetically synthesized single-walled carbon nanotube chitosan nanocomposite for bone regeneration,” *International journal of nanomedicine*, vol. 7, p. 2087, 2012.

[46] Z. Qin and M. Buehler, “Bioinspired design of functionalised graphene,” *Molecular Simulation*, vol. 38, no. 8–9, pp. 695–703, 2012.

[47] S. Amini and A. Miserez, “Wear and abrasion resistance selection maps of biological materials,” *Acta biomaterialia*, vol. 9, no. 8, pp. 7895–7907, 2013.

[48] J. Wang and R. Rai, “Classification of Bio-Inspired Periodic Cubic Cellular Materials Based on Compressive Deformation Behaviors of 3D Printed Parts and FE Simulations,” in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, p. V007T06A003–V007T06A003.

[49] K. Liu, Y. Tian, and L. Jiang, “Bio-inspired superoleophobic and smart materials: design, fabrication, and application,” *Progress in Materials Science*, vol. 58, no. 4, pp. 503–564, 2013.

[50] X. Zhang, Z. Li, K. Liu, and L. Jiang, “Bioinspired multifunctional foam with self-cleaning and oil/water separation,” *Advanced Functional Materials*, vol. 23, no. 22, pp. 2881–2886, 2013.

[51] T. Jiang, Z. Guo, and W. Liu, “Biomimetic superoleophobic surfaces: focusing on their fabrication and applications,” *Journal of Materials Chemistry A*, vol. 3, no. 5, pp. 1811–1827, 2015.

[52] L. Zhang, L. Li, and Z.-M. Dang, “Bio-inspired durable, superhydrophobic magnetic particles for oil/water separation,” *Journal of colloid and interface science*, vol. 463, pp. 266–271, 2016.

[53] A. G. Fane, R. Wang, and M. X. Hu, “Synthetic membranes for water purification: status and future,” *Angewandte Chemie International Edition*, vol. 54, no. 11, pp. 3368–3386, 2015.

[54] K. Liu and L. Jiang, “Multifunctional integration: from biological to bio-inspired materials,” *Acs Nano*, vol. 5, no. 9, pp. 6786–6790, 2011.

[55] S. Sareh, J. Rossiter, A. Conn, K. Drescher, and R. E. Goldstein, “Swimming like algae: biomimetic soft artificial cilia,” *Journal of the Royal Society Interface*, p. rsif20120666, 2012.

[56] E. J. Gendreau *et al.*, “Camels and Fennec Foxes: A Case Study on Biologically Inspired Design of Sand Traction Systems,” in *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2015, p. V007T06A002–V007T06A002.

[57] M. Vandaele, B. S. Joyce, and P. A. Tarazaga, “Design and Characterization of Piezo-Based Stereocilia,” in *ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2013, p. V002T06A017–V002T06A017.

[58] A. Ishfaque and B. Kim, “Design of Centrally Supported Biomimetic MEMS Microphone for Acoustic Source Localization,” in *ASME 2015 International Mechanical Engineering Congress and Exposition*, 2015, p. V010T13A025–V010T13A025.

[59] L. Burns, A. P. Mouritz, D. Pook, and S. Feih, “Bio-inspired hierarchical design of composite T-joints with improved structural properties,” *Composites Part B: Engineering*, vol. 69, pp. 222–231, 2015.

[60] Z. Chen, Q. Guo, C. Majidi, W. Chen, D. J. Srolovitz, and M. Haataja, “Bistable Structures Exhibiting Snap-Through Instability: From Slap Bracelets to the Venus Flytrap,” in *ASME 2012 Summer Bioengineering Conference*, 2012, pp. 749–750.

[61] C. Yang, C. Song, W. Shang, P. Tao, and T. Deng, “Flexible heat pipes with integrated bioinspired design,” *Progress in Natural Science: Materials International*, vol. 25, no. 1, pp. 51–57, 2015.

[62] P. Kumar *et al.*, “GPS based navigation design for a bio inspired precision air drop system,” in *Computing, Communication and Automation (ICCCA), 2016 International Conference on*, 2016, pp. 902–906.

[63] E. Vermisso, “The fabrication of fabrication: a second order design process,” *International Journal of Architectural Computing*, vol. 10, no. 3, pp. 401–422, 2012.

[64] J. K. Nagel and R. B. Stone, “A computational approach to biologically inspired design,” *AI EDAM*, vol. 26, no. 2, pp. 161–176, 2012.

[65] M. W. Glier, D. A. McAdams, and J. S. Linsey, “An experimental investigation of analogy formation using the engineering-to-biology thesaurus,” in *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2013, p. V005T06A007–V005T06A007.

[66] S. S. Vattam, M. E. Helms, and A. K. Goel, “A content account of creative analogies in biologically inspired design,” *AI EDAM*, vol. 24, no. 4, pp. 467–481, 2010.

[67] K. Fu, D. Moreno, M. Yang, and K. L. Wood, “Bio-inspired design: an overview investigating open questions from the broader field of design-by-analogy,” *Journal of Mechanical Design*, vol. 136, no. 11, p. 111102, 2014.

[68] A. K. Goel *et al.*, “Design patterns and cross-domain analogies in biologically inspired sustainable design,” in *2011 AAAI Spring Symposium Series*, 2011.

[69] K. D. Jones, C. J. Bradshaw, J. Papadopoulos, and M. F. Platzer, “Bio-inspired design of flapping-wing micro air vehicles,” *The Aeronautical Journal*, vol. 109, no. 1098, pp. 385–393, 2005.

[70] A. Matta and J. Bayandor, “An Analytical Study on the Effect of Active Wing Folding and Twist on the Aerodynamic Performance and Energy Consumption of a Bio-Inspired Ornithopter,” in *ASME 2016 Fluids Engineering Division Summer Meeting collocated with the ASME 2016 Heat Transfer Summer Conference and the ASME 2016 14th International Conference on Nanochannels, Microchannels, and Minichannels*, 2016, p. V01AT12A005–V01AT12A005.

[71] H. Hailin and L. Bing, “Geometric design of a bio-inspired flapping wing mechanism based on bennett-derived 6R deployable mechanisms,” in *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2014, p. V05BT08A042–V05BT08A042.

[72] D. Talarico and K. Hynes, “Bio-Inspired Wind Energy Harvester,” in *ASME 2012 6th International Conference on Energy Sustainability collocated with the ASME 2012 10th International Conference on Fuel Cell Science, Engineering and Technology*, 2012, pp. 1411–1414.

[73] J. Joy, T. H. New, and I. H. Ibrahim, “A computational study on flow separation control of humpback whale inspired sinusoidal hydrofoils,” *International Journal of Mechanical and Mechatronics Engineering*, vol. 10, no. 2, pp. 357–362, 2016.

[74] J. Hu, Q. Xiao, and V. T. Nguyen, “An Exploration of a PASSIVE Articulated Fish-Like System,” in *ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering*, 2013, p. V005T06A059–V005T06A059.

[75] A. Moosavian, L. L. Gamble, A. M. Pankonien, and D. J. Inman, “Bio-inspired Coupling of Camber and Sweep in Morphing Wings,” in *ASME 2016 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2016, p. V002T06A007–V002T06A007.

[76] K. Isaac and T. Swanson, “Biologically inspired wing leading edge for enhanced wind turbine and aircraft performance,” in *6th AIAA Theoretical Fluid Mechanics Conference*, 2011, p. 3533.

[77] G. Molinari, M. Quack, A. F. Arrieta, M. Morari, and P. Ermanni, “Design and realization of a compliant adaptable wing,” in *ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2014, p. V002T04A010–V002T04A010.

[78] E. Fisher *et al.*, “A bio-inspired aircraft design concept,” in *ASME 2012 Fluids Engineering Division Summer Meeting collocated with the ASME 2012 Heat Transfer Summer Conference and the ASME 2012 10th International Conference on Nanochannels, Microchannels, and Minichannels*, 2012, pp. 855–862.

[79] A. Dhruv, C. J. Blower, and A. M. Wickenheiser, “A Three Dimensional Iterative Panel Method for Bio-Inspired Multi-Body Wings,” in *ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2014, p. V002T06A014–V002T06A014.

[80] S. C. Burgess and A. C. Etoundi, “Performance maps for a bio-inspired robotic condylar hinge joint,” *Journal of Mechanical Design*, vol. 136, no. 11, p. 115002, 2014.

[81] E. Mattar, “A survey of bio-inspired robotics hands implementation: New directions in dexterous manipulation,” *Robotics and Autonomous Systems*, vol. 61, no. 5, pp. 517–544, 2013.

[82] F. Maghooa, A. Stilli, Y. Noh, K. Althoefer, and H. A. Wurdemann, “Tendon and pressure actuation for a bio-inspired manipulator based on an antagonistic principle,” in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, 2015, pp. 2556–2561.

[83] S. Guo, L. Shi, N. Xiao, and K. Asaka, “A biomimetic underwater microrobot with multifunctional locomotion,” *Robotics and Autonomous Systems*, vol. 60, no. 12, pp. 1472–1483, 2012.

[84] W. Gao *et al.*, “Bioinspired helical microswimmers based on vascular plants,” *Nano letters*, vol. 14, no. 1, pp. 305–310, 2013.

[85] B. F. Seitz *et al.*, “Bio-inspired mechanisms for inclined locomotion in a legged insect-scale robot,” in *Robotics and Biomimetics (ROBIO), 2014 IEEE International Conference on*, 2014, pp. 791–796.

[86] H. Fang, S. Li, K. W. Wang, and J. Xu, “Locomotion gait design of an earthworm-like robot based on multi-segment fluidic flexible matrix composite structures,” in *ASME 2013 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2013, p. V002T06A003–V002T06A003.

[87] A. Garcia, S. Priya, and P. Marek, “Understanding the locomotion and dynamic controls for millipedes: part 1—kinematic analysis of millipede movements,” in *ASME 2015 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2015, p. V002T06A005–V002T06A005.

[88] A. Pagano, B. Leung, B. Chien, T. Yan, A. Wissa, and S. Tawfick, “Multi-stable origami structure for crawling locomotion,” in *ASME 2016 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, 2016, p. V002T06A005–V002T06A005.

[89] J. Yu, R. Ding, Q. Yang, M. Tan, W. Wang, and J. Zhang, “On a bio-inspired amphibious robot capable of multimodal motion,” *IEEE/ASME Transactions On Mechatronics*, vol. 17, no. 5, pp. 847–856, 2012.

[90] G. D. Weymouth, V. Subramaniam, and M. S. Triantafyllou, “Ultra-fast escape maneuver of an octopus-inspired robot,” *Bioinspiration & biomimetics*, vol. 10, no. 1, p. 016016, 2015.

[91] F. Boyer, S. Ali, and M. Porez, “Macrocontinuous dynamics for hyperredundant robots: application to kinematic locomotion bioinspired by elongated body animals,” *IEEE Transactions on Robotics*, vol. 28, no. 2, pp. 303–317, 2012.

[92] O. Ly, M. Lapeyre, and P.-Y. Oudeyer, “Bio-inspired vertebral column, compliance and semi-passive dynamics in a lightweight humanoid robot,” in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, 2011, pp. 1465–1472.

[93] S. Kim, C. Laschi, and B. Trimmer, “Soft robotics: a bioinspired evolution in robotics,” *Trends in biotechnology*, vol. 31, no. 5, pp. 287–294, 2013.

[94] J. Oeffner and G. V. Lauder, “The hydrodynamic function of shark skin and two biomimetic applications,” *Journal of Experimental Biology*, vol. 215, no. 5, pp. 785–795, 2012.

[95] W. Saab and P. Ben-Tzvi, “Design and Analysis of a Robotic Modular Leg Mechanism,” in *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2016, p. V05AT07A062–V05AT07A062.

[96] J. Zhang, G. Song, Y. Li, G. Qiao, A. Song, and A. Wang, “A bio-inspired jumping robot: Modeling, simulation, design, and experimental results,” *Mechatronics*, vol. 23, no. 8, pp. 1123–1140, 2013.

[97] L. Cui, P. Cheong, R. Adams, and T. Johnson, “Ambot: A bio-inspired amphibious robot for monitoring the swan-canning estuary system,” *Journal of Mechanical Design*, vol. 136, no. 11, p. 115001, 2014.

[98] A. Kapilavai, R. E. Mohan, and N. Tan, “Bioinspired design: A case study of reconfigurable crawling-rolling robot,” in *DS 80-2 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 2: Design Theory and Research Methodology Design Processes, Milan, Italy, 27-30.07. 15*, 2015.

[99] P. Phamduy, R. Le Grand, and M. Porfiri, “Design of a Biomimetic Robotic Fish Controlled by a Touch Screen,” in *ASME 2014 Dynamic Systems and Control Conference*, 2014, p. V002T29A002–V002T29A002.

[100] F. Corucci, M. Calisti, H. Hauser, and C. Laschi, “Novelty-based evolutionary design of morphing underwater robots,” in *Proceedings of the 2015 annual conference on Genetic and Evolutionary Computation*, 2015, pp. 145–152.

[101] W. J. Larson and J. R. Wertz, “Space mission analysis and design,” Microcosm, Inc., Torrance, CA (US), 1992.

[102] G. Radice, R. Wuilbercq, and G. Cafiero, “T-SMAD: a Concurrent Design Tool for Space Mission Analysis and Design,” *Frontiers in Aerospace Engineering*, vol. 3, no. 1, pp. 1–6, 2014.

[103] J. G. Bellingham and K. Rajan, “Robotics in remote and hostile environments,” *Science*, vol. 318, no. 5853, pp. 1098–1102, 2007.

[104] S. Lake, D. Liley, R. Still, and A. Swash, *Britain’s Habitats: A Guide to the Wildlife Habitats of Britain and Ireland*. Princeton University Press, 2015.

[105] R. M. Starr, *Oregon Marine and Estuarine Habitat Classification Systems*. Oregon Natural Area Preserves Advisory Committee, 1979.

[106] D. Bottom, O. L. Conservation, and D. Commission, “Habitat classification and inventory methods for the management of Oregon estuaries,” 1979.

[107] M. L. Guarinello, E. J. Shumchenia, and J. W. King, “Marine habitat classification for ecosystem-based management: a proposed hierarchical framework,” *Environmental management*, vol. 45, no. 4, pp. 793–806, 2010.

[108] L. Rivard and C. Hehner-Rivard, “Complex Terrain Categories,” in *Complex Terrain Mapping*, Springer, 2014, pp. 5–291.

[109] B. K. Ahlborn, *Zoological physics: Quantitative models of body design, actions, and physical limitations of animals*. Springer Science & Business Media, 2006.

[110] A. A. Biewener, *Animal locomotion*. Oxford University Press, 2003.

[111] A. A. Paranjape, M. R. Dorothy, S.-J. Chung, and K. D. Lee, “A flight mechanics-centric review of bird-scale flapping flight,” *International Journal Aeronautical and Space Sciences*, vol. 13, no. 3, pp. 267–281, 2012.

[112] R. Von Busse, A. Hedenström, Y. Winter, and L. C. Johansson, “Kinematics and wing shape across flight speed in the bat, Leptonycteris yerbabuenae,” *Biology open*, vol. 1, no. 12, pp. 1226–1238, 2012.

[113] D. K. Riskin, A. Bergou, K. S. Breuer, and S. M. Swartz, “Upstroke wing flexion and the inertial cost of bat flight,” *Proceedings of the Royal Society of London B: Biological Sciences*, vol. 279, no. 1740, pp. 2945–2950, 2012.

[114] C. E. Kovacs and R. A. Meyers, “Anatomy and histochemistry of flight muscles in a wing-propelled diving bird, the Atlantic puffin, Fratercula arctica,” *Journal of Morphology*, vol. 244, no. 2, pp. 109–125, 2000.

[115] K. V. Reynolds, A. L. Thomas, and G. K. Taylor, “Wing tucks are a response to atmospheric turbulence in the soaring flight of the steppe eagle Aquila nipalensis,” *Journal of The Royal Society Interface*, vol. 11, no. 101, p. 20140645, 2014.

[116] P. S. Segre *et al.*, “Hydrodynamic properties of fin whale flippers predict maximum rolling performance,” *Journal of Experimental Biology*, vol. 219, no. 21, pp. 3315–3320, 2016.

[117] P. W. Weber, L. E. Howle, M. M. Murray, and F. E. Fish, “Lift and drag performance of odontocete cetacean flippers,” *Journal of Experimental Biology*, vol. 212, no. 14, pp. 2149–2158, 2009.

[118] N. Mazouchova, “Principles of fin and flipper locomotion on granular media,” PhD Thesis, Georgia Institute of Technology, 2012.

[119] J. N. Garrett and F. E. Fish, "Kinematics of terrestrial locomotion in harbor seals and gray seals: Importance of spinal flexion by amphibious phocids," *Marine Mammal Science*, vol. 31, no. 2, pp. 459–478, 2015.

[120] B. Sudki, M. Lauria, and F. Noca, "Marine propulsor based on a three-degree-of-freedom actuated spherical joint," in *Proceedings of the 3rd International Symposium on Marine Propulsors*, 2013.

[121] A. N. Langville and C. D. Meyer, *Who's# 1?: the science of rating and ranking*. Princeton University Press, 2012.

[122] J. C. Gower, "A general coefficient of similarity and some of its properties," *Biometrics*, pp. 857–871, 1971.

[123] D. Clay, *Linear Algebra and its Applications*, 4th ed. Pearson, 2012.

[124] A-Z-Animals.com, "Polar Regions." [Online]. Available: https://a-z-animals.com/reference/polar-regions/. [Accessed: 06-Mar-2018].

[125] A-Z-Animals.com, "Coniferous Forest, Picture 5 of 6." [Online]. Available: https://a-z-animals.com/reference/coniferous-forest/pictures/3644/. [Accessed: 06-Mar-2018].

[126] A-Z-Animals.com, "Grassland." [Online]. Available: https://a-z-animals.com/reference/grassland/. [Accessed: 06-Mar-2018].

[127] "BBC Nature - Taiga videos, news and facts." [Online]. Available: http://www.bbc.co.uk/nature/habitats/Taiga. [Accessed: 06-Mar-2018].

[128] D. Ullman, *The mechanical design process*. McGraw-Hill Science/Engineering/Math, 2009.

[129] "MRL | Top View of the Stingray." .

[130] "ClimbingAdhesionHome | Biomimetics and Dextrous Manipulation Lab." [Online]. Available: http://bdml.stanford.edu/Main/ClimbingAdhesionHome. [Accessed: 05-Jun-2018].

[131] "SmartBird | Festo Corporate." [Online]. Available: https://www.festo.com/group/en/cms/10238.htm. [Accessed: 05-Jun-2018].

[132] D. Jackson, M. Miller, B. Johnston, and R. Stone, "Obtaining Environmental Classifications and Animal Fitness Scores or the use of Aero/Hydro Vehicle Design for Complex Environments," *Prepared for Publication*.

[133] J. H. Steiger, “Tests for comparing elements of a correlation matrix.,” *Psychological bulletin*, vol. 87, no. 2, p. 245, 1980.

[134] J. Lee Rodgers and W. A. Nicewander, “Thirteen ways to look at the correlation coefficient,” *The American Statistician*, vol. 42, no. 1, pp. 59–66, 1988.

[135] C. D. Dzubian and E. C. Shirkey, “When is a correlation matrix appropriate for factor analysis,” *Psychological Bulletin*, vol. 81, no. 6, pp. 358–361, 1974.

[136] “Statistical Significance of the Matrix Correlation... - Google Scholar.” [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C38&q=Statistical+Significance+of+the+Matrix+Correlation+Coefficient+for+Comparing+Independent+Phylogenetic+Trees&btnG=. [Accessed: 20-May-2018].

[137] D. G. Higgins and P. M. Sharp, “Fast and sensitive multiple sequence alignments on a microcomputer,” *Bioinformatics*, vol. 5, no. 2, pp. 151–153, 1989.

[138] M. Cooper and J. Foote, “Summarizing video using non-negative similarity matrix factorization,” in *Multimedia Signal Processing, 2002 IEEE Workshop on*, 2002, pp. 25–28.

[139] J. M. Levin, B. Robson, and J. Garnier, “An algorithm for secondary structure determination in proteins based on sequence similarity,” *FEBS letters*, vol. 205, no. 2, pp. 303–308, 1986.

[140] G. Wu, E. Y. Chang, and Z. Zhang, “An analysis of transformation on non-positive semidefinite similarity matrix for kernel machines,” in *Proceedings of the 22nd International Conference on Machine Learning*, 2005, vol. 8.

[141] N. J. Higham, “Computing the nearest correlation matrix—a problem from finance,” *IMA journal of Numerical Analysis*, vol. 22, no. 3, pp. 329–343, 2002.

[142] C.-T. Chen, “Extensions of the TOPSIS for group decision-making under fuzzy environment,” *Fuzzy sets and systems*, vol. 114, no. 1, pp. 1–9, 2000.

[143] R. Ezzati, T. Allahviranloo, S. Khezerloo, and M. Khezerloo, “An approach for ranking of fuzzy numbers,” *Expert Systems with Applications*, vol. 39, no. 1, pp. 690–695, 2012.

[144] D. Wu and J. M. Mendel, “A comparative study of ranking methods, similarity measures and uncertainty measures for interval type-2 fuzzy sets,” *Information Sciences*, vol. 179, no. 8, pp. 1169–1192, 2009.

[145] P. Andersen and N. C. Petersen, “A procedure for ranking efficient units in data envelopment analysis,” *Management science*, vol. 39, no. 10, pp. 1261–1264, 1993.

[146] M. Kulkarni and M. Lingayat, “Effective Product Ranking Method based on Opinion Mining,” *International Journal of Computer Applications*, vol. 120, no. 18, 2015.

[147] D. Kee and W. Karwowski, “Ranking systems for evaluation of joint and joint motion stressfulness based on perceived discomforts,” *Applied ergonomics*, vol. 34, no. 2, pp. 167–176, 2003.

[148] B. Alma, E. Coşkun, and E. Övendireli, “University Ranking Systems and Proposal of a Theoretical Framework for Ranking of Turkish Universities: A Case of Management Departments,” *Procedia-Social and Behavioral Sciences*, vol. 235, pp. 128–138, 2016.

[149] “2-D correlation coefficient - MATLAB corr2.” [Online]. Available: https://www.mathworks.com/help/images/ref/corr2.html. [Accessed: 25-May-2018].

[150] “General Thrust Equation.” [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/thrsteq.html. [Accessed: 16-Jun-2018].

[151] “The Lift Equation.” [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/lifteq.html. [Accessed: 16-Jun-2018].

[152] “Terminal Velocity.” [Online]. Available: https://www.grc.nasa.gov/www/k-12/airplane/termv.html. [Accessed: 16-Jun-2018].

[153] Smithsonian Channel, *Gannets Plunge into the Sea*. .

[154] M. Rosén and A. Hedenström, “Gliding flight in a jackdaw,” p. 14.

[155] “L/D Ratio.” [Online]. Available: https://www.grc.nasa.gov/www/K-12/airplane/ldrat.html. [Accessed: 18-Jun-2018].

[156] R. Stengel, “Gliding, Climbing, and Turning Flight Performance!,” p. 24.

[157] V. A. Tucker and G. C. Parrott, *Printed in Great Britain AERODYNAMICS OF GLIDING FLIGHT IN A FALCON AND OTHER BIRDS*. 1969.

[158] Z. Ákos, M. Nagy, S. Leven, and T. Vicsek, “Thermal soaring flight of birds and unmanned aerial vehicles,” *Bioinspiration & Biomimetics*, vol. 5, no. 4, p. 045003, Dec. 2010.

[159] C. P. Robert and G. Casella, “Monte Carlo Statistical Methods,” p. 85.

[160] "Monte Carlo Simulation - Christopher Z. Mooney - Google Books." [Online]. Available: https://books.google.com/books?hl=en&lr=&id=lFhvCAAAQBAJ&oi=fnd&pg=PR7&dq=monte+carlo+simulation&ots=KECuMwGlMe&sig=29NcUMUVQ1CW_ByZhFfyrXdaPQk#v=onepage&q=assumption&f=false. [Accessed: 11-Jun-2018].

[161] "Guiding Principles for Monte Carlo Analysis," p. 39.

[162] "Random Number Generation - MATLAB & Simulink." [Online]. Available: https://www.mathworks.com/help/matlab/random-number-generation.html. [Accessed: 18-Jun-2018].

[163] K. Oldenbroek and L. Van Der Waaij, "Textbook Animal Breeding and Genetics." [Online]. Available: https://wiki.groenkennisnet.nl/display/TAB/Textbook+Animal+Breeding+and+Genetics. [Accessed: 18-Jun-2018].

[164] D. Jackson, M. Miller, B. Johnstone, C. Hoyle, and R. Stone, "Producing Animal and Environmental Simularity Matrices and Quantifiable Animal Mobility Functions For An Aero/Hydro Bio-Inspired Vehicle Design," *Prepared for Publication*.

[165] P.-E. Fayemi, K. Wanieck, C. Zollfrank, N. Maranzana, and A. Aoussat, "Biomimetics: process, tools and practice," *Bioinspiration & biomimetics*, vol. 12, no. 1, p. 011002, 2017.

[166] "AskNature - Innovation Inspired by Nature," *AskNature*. [Online]. Available: https://asknature.org/. [Accessed: 01-Jul-2018].

[167] "AskNature," *Biomimicry Institute*. [Online]. Available: https://biomimicry.org/asknature/. [Accessed: 01-Jul-2018].

[168] "Design Repository | Design Engineering Lab | Oregon State University." [Online]. Available: https://design.engr.oregonstate.edu/repo. [Accessed: 01-Jul-2018].

[169] "Washington NatureMapping Program." [Online]. Available: http://naturemappingfoundation.org/natmap/. [Accessed: 01-Jul-2018].

[170] "NatureMapping NatureTracker Technology." [Online]. Available: http://naturemappingfoundation.org/natmap/tech/. [Accessed: 01-Jul-2018].

[171] K. Pedersen *et al.*, "VALIDATING DESIGN METHODS & RESEARCH: THE VALIDATION SQUARE," p. 14, 2000.

[172] K. E. Lewis, W. Chen, and L. C. Schmidt, Eds., *Decision Making in Engineering Design*. Three Park Avenue New York, NY 10016-5990: ASME, 2006.

[173] D. Frey and C. Dym, “Validation of design methods: lessons from medicine,” *Research in Engineering Design*, vol. 17, no. 1, pp. 45–57, Jun. 2006.

[174] C. A. Versos and D. A. Coelho, “Biologically inspired design: methods and validation,” in *Industrial Design-New Frontiers*, Intech, 2011.

[175] “Seabreacher Y | Seabreacher | The Ultimate Diving Machine.” .

[176] “Aqua_ray | Festo Corporate.” [Online]. Available: https://www.festo.com/group/en/cms/10246.htm. [Accessed: 02-Jul-2018].

[177] E. Keshavarzi, M. McIntire, K. Goebel, I. Y. Tumer, and C. Hoyle, “Resilient System Design Using Cost-Risk Analysis With Functional Models,” p. V02AT03A043, Aug. 2017.

[178] E. Keshavarzi, M. McIntire, and C. Hoyle, “A dynamic design approach using the Kalman filter for uncertainty management,” *AI EDAM*, vol. 31, no. 2, pp. 161–172, 2017.

[179] E. Keshavarzi, M. McIntire, and C. Hoyle, “Dynamic design using the Kalman filter for flexible systems with epistemic uncertainty,” in *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 2015, p. V02BT03A019–V02BT03A019.

[180] E. Keshavarzi, “Resilient Design for Complex Engineered Systems in the Early Design Phase,” 2018.

[181] “Great Horned Owl,” *Environment Alaska*. [Online]. Available: http://environmentalaska.us/great-horned-owl.html. [Accessed: 08-Mar-2018].

[182] “Great Horned Owl Life History, All About Birds, Cornell Lab of Ornithology.” [Online]. Available: https://www.allaboutbirds.org/guide/Great_Horned_Owl/lifehistory. [Accessed: 08-Mar-2018].

[183] “California NatureMapping - Barn Owl Fact Sheet.” [Online]. Available: http://naturemappingfoundation.org/natmap/ca/facts/birds/barn_owl.html. [Accessed: 01-Jul-2018].

[184] “Great Horned Owl | National Geographic.” [Online]. Available: https://www.nationalgeographic.com/animals/birds/g/great-horned-owl/?beta=true. [Accessed: 02-Jul-2018].

[185] M. W. COLLOPY and T. C. EDWARDS, “TERRITORY SIZE, ACTIVITY BUDGET, AND ROLE OF UNDULATING FLIGHT IN NESTING GOLDEN EAGLES,” p. 9, 1989.

[186] “Golden Eagle | National Geographic,” *Animals*, 10-Jun-2011. [Online]. Available: https://www.nationalgeographic.com/animals/birds/g/golden-eagle/. [Accessed: 02-Jul-2018].

[187] “CWR - orca,” *Orcas // Killer Whales | United States | Center For Whale Research*. [Online]. Available: https://www.whaleresearch.com/about-orcas. [Accessed: 02-Jul-2018].

[188] “Orca (Killer Whale) | National Geographic,” *Animals*, 10-Sep-2010. [Online]. Available: https://www.nationalgeographic.com/animals/mammals/o/orca/. [Accessed: 02-Jul-2018].

[189] “Gentoo Penguin | National Geographic,” *Animals*, 08-Nov-2010. [Online]. Available: https://www.nationalgeographic.com/animals/birds/g/gentoo-penguin/. [Accessed: 02-Jul-2018].

[190] “Gentoo Penguin,” *Ocean Park Hong Kong*, 25-Jul-2016. [Online]. Available: https://www.oceanpark.com.hk/en/conservation/animal-and-plant-guide/gentoo-penguin. [Accessed: 02-Jul-2018].

[191] A. W. Diamond and E. A. Schreiber, “Magnificent Frigatebird (Fregata magnificens),” *The Birds of North America Online*, 2002.

[192] “Magnificent Frigatebird Identification, All About Birds, Cornell Lab of Ornithology.” [Online]. Available: https://www.allaboutbirds.org/guide/Magnificent_Frigatebird/id. [Accessed: 02-Jul-2018].

[193] “Harp Seal.” [Online]. Available: https://oceanwide-expeditions.com/to-do/wildlife/harp-seal. [Accessed: 08-Mar-2018].

[194] “Harp Seal | Facts, pictures & more about Harp Seals.” [Online]. Available: https://oceanwide-expeditions.com/to-do/wildlife/harp-seal. [Accessed: 01-Jul-2018].

[195] "Harp Seal | National Geographic." [Online]. Available: https://www.nationalgeographic.com/animals/mammals/h/harp-seal/?beta=true. [Accessed: 02-Jul-2018].

[196] "Harp seal | mammal," *Encyclopedia Britannica*. [Online]. Available: https://www.britannica.com/animal/harp-seal. [Accessed: 02-Jul-2018].

[197] A. Tilley, "FUNCTIONAL ECOLOGY OF THE SOUTHERN STINGRAY, DASYATIS AMERICANA," p. 174.

[198] "Southern Stingray - Dasyatis americana - Stingrays - - Caribbean Reefs." [Online]. Available: http://reefguide.org/carib/southernray.html. [Accessed: 02-Jul-2018].

[199] "Stingray," *Kids*. [Online]. Available: https://kids.nationalgeographic.com/animals/stingray/. [Accessed: 02-Jul-2018].

[200] T. Dewey and M. Potter, "Falco peregrinus (peregrine falcon)," *Animal Diversity Web*. [Online]. Available: http://animaldiversity.org/accounts/Falco_peregrinus/. [Accessed: 02-Jul-2018].

[201] B. Ponitz, A. Schmitz, D. Fischer, H. Bleckmann, and C. Brücker, "Diving-Flight Aerodynamics of a Peregrine Falcon (Falco peregrinus)," *PLOS ONE*, vol. 9, no. 2, p. e86506, Feb. 2014.

[202] V. A. TUCKER, "GLIDING FLIGHT: SPEED AND ACCELERATION OF IDEAL FALCONS DURING DIVING AND PULL OUT," p. 12.

[203] "Peregrine Falcon Identification, All About Birds, Cornell Lab of Ornithology." [Online]. Available: https://www.allaboutbirds.org/guide/Peregrine_Falcon/id. [Accessed: 02-Jul-2018].

[204] C. M. Bovery and J. Wyneken, "Seasonal Variation in Sea Turtle Density and Abundance in the Southeast Florida Current and Surrounding Waters," *PLoS One*, vol. 10, no. 12, Dec. 2015.

[205] "Green Sea Turtle," *Kids*. [Online]. Available: https://kids.nationalgeographic.com/animals/green-sea-turtle/. [Accessed: 01-Jul-2018].

[206] "Green Turtle | Sea Turtles | Species | WWF," *World Wildlife Fund*. [Online]. Available: https://www.worldwildlife.org/species/green-turtle. [Accessed: 02-Jul-2018].

[207] dfg.webmaster@alaska.gov, “Steller Sea Lion Species Profile, Alaska Department of Fish and Game.” [Online]. Available: http://www.adfg.alaska.gov/index.cfm?adfg=stellersealion.printerfriendly. [Accessed: 02-Jul-2018].

[208] N. Fisheries, “Steller Sea Lion (Eumetopias jubatus) :: NOAA Fisheries.” [Online]. Available: http://www.nmfs.noaa.gov/pr/species/mammals/sealions/steller-sea-lion.html. [Accessed: 02-Jul-2018].

[209] “Steller Sea Lion | National Geographic,” *Animals*, 11-Nov-2010. [Online]. Available: https://www.nationalgeographic.com/animals/mammals/s/steller-sea-lion/. [Accessed: 02-Jul-2018].

[210] J. Bhatia, “Leptonycteris yerbabuenae (lesser long-nosed bat),” *Animal Diversity Web*. [Online]. Available: http://animaldiversity.org/accounts/Leptonycteris_yerbabuenae/. [Accessed: 02-Jul-2018].

[211] “Species Profile for Lesser Long-Nosed bat (Leptonycteris curasoae yerbabuenae).” [Online]. Available: https://ecos.fws.gov/ecp0/profile/speciesProfile?spcode=A0AD. [Accessed: 02-Jul-2018].

[212] L. Pajerski, “Accipiter gentilis (northern goshawk),” *Animal Diversity Web*. [Online]. Available: http://animaldiversity.org/accounts/Accipiter_gentilis/. [Accessed: 02-Jul-2018].

[213] J. RaptorRes, “THE JOURNAL OF RAPTOR RESEARCH,” vol. 22, no. 3, p. 4.

[214] “Manatee Facts,” *Save the Manatee Club*. .

[215] “Manatees | National Geographic,” *Animals*, 11-Nov-2010. [Online]. Available: https://www.nationalgeographic.com/animals/mammals/group/manatees/. [Accessed: 02-Jul-2018].

[216] “8 things you didn’t know about manatees,” *PBS NewsHour*, 26-Nov-2014. [Online]. Available: https://www.pbs.org/newshour/science/8-things-didnt-know-manatees. [Accessed: 02-Jul-2018].

[217] I. mindcomet com MindComet, “Physical Characteristics.” [Online]. Available: https://seaworld.org/en/animal-info/animal-infobooks/walrus/physical-characteristics. [Accessed: 02-Jul-2018].

[218] “Shortfin Mako Sharks, Isurus oxyrinchus,” *MarineBio.org*. [Online]. Available: http://marinebio.org/species.asp?id=36. [Accessed: 09-Jul-2018].

[219] M. B. R. K. S. Tullgren, “Isurus oxyrinchus (Mackerel porbeagle),” *Animal Diversity Web*. [Online]. Available: http://animaldiversity.org/accounts/Isurus_oxyrinchus/. [Accessed: 09-Jul-2018].

[220] L. M. Nichol, J. C. Watson, and Committee on the Status of Endangered Wildlife in Canada, *COSEWIC assessment and status report on the sea otter, Enhydra lutris, in Canada.* Ottawa: Committee on the Status of Endangered Wildlife in Canada, 2007.

[221] “Species Profile for Northern Sea Otter (Enhydra lutris kenyoni).” [Online]. Available: https://ecos.fws.gov/ecp0/profile/speciesProfile?spcode=A0HK. [Accessed: 09-Jul-2018].

[222] J. A. R. R. A. Gunderson, “Enhydra lutris (sea otter),” *Animal Diversity Web*. [Online]. Available: http://animaldiversity.org/accounts/Enhydra_lutris/. [Accessed: 09-Jul-2018].

[223] M. A. P. B. 129 Gr, Canyon, and A. 86023 P.-7888 C. Us, “Grand Canyon National Park (U.S. National Park Service).” [Online]. Available: https://www.nps.gov/grca/index.htm. [Accessed: 01-Jul-2018].

[224] M. A. P. B. 129 Gr, Canyon, and A. 86023 P.-7888 C. Us, “Park Statistics - Grand Canyon National Park (U.S. National Park Service).” [Online]. Available: https://www.nps.gov/grca/learn/management/statistics.htm. [Accessed: 02-Jul-2018].

[225] “Wind speed Grand Canyon National Park - Observations | Arizona Weather History.” [Online]. Available: https://www.weatheronline.co.uk/weather/maps/city?LANG=en&WMO=x0049&ART=WST&CONT=namk&R=0&LEVEL=150&REGION=0016&LAND=AZ&NOREGION=0&MOD=&TMX=&TMN=&SON=&PRE=&MONAT=&OFFS=&SORT=. [Accessed: 02-Jul-2018].

[226] C. G. S. T.-A.-C. Ltd, “Arctic Ocean | Sea Temperatures.” [Online]. Available: http://www.seatemperature.org/arctic-ocean. [Accessed: 02-Jul-2018].

[227] “Google Maps,” *Google Maps*. [Online]. Available: https://www.google.com/maps/place/Grand+Canyon+National+Park/@36.1148804,-112.096036,3439m/data=!3m1!1e3!4m12!1m6!3m5!1s0x0:0x1f38a9bec9912029!2sGrand+Canyon+National+Park!8m2!3d36.1069652!4d-112.1129972!3m4!1s0x0:0x1f38a9bec9912029!8m2!3d36.1069652!4d-112.1129972. [Accessed: 02-Jul-2018].

[228] “Ocean Motion : Data Resources : Ocean Surface Current Visualizer.” [Online]. Available: http://oceanmotion.org/html/resources/oscar.htm. [Accessed: 09-Mar-2018].

[229] “Coral Reefs.” [Online]. Available: http://www.seos-project.eu/modules/coralreefs/coralreefs-c01-p03.html. [Accessed: 02-Jul-2018].

[230] “What is the Difference Between a Temperate & Tropical Ocean? | Sciencing.” [Online]. Available: https://sciencing.com/difference-between-temperate-tropical-ocean-8035716.html. [Accessed: 02-Jul-2018].

[231] “How do we measure the density of sea water?” [Online]. Available: http://globec.whoi.edu/globec-dir/sea_water_density_description.html. [Accessed: 02-Jul-2018].

[232] “Coral of Canada: Atlantic Deep-Ocean Coral | Earth Rangers Wild Wire Blog,” *Earth Rangers*, 21-Mar-2014. .

[233] “Taiga Climate.” [Online]. Available: http://www.blueplanetbiomes.org/taiga_climate.htm. [Accessed: 02-Jul-2018].

[234] “Climate Taiga Ranges,” *meteoblue*. [Online]. Available: https://www.meteoblue.com/en/weather/forecast/modelclimate/taiga-ranges_canada_6161165. [Accessed: 02-Jul-2018].

[235] J. C. Jenkins, D. C. Chojnacky, L. S. Heath, and R. A. Birdsey, “Comprehensive database of diameter-based biomass regressions for North American tree species,” U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA, NE-GTR-319, 2004.

[236] “Kelp Forests - A Description | Office of National Marine Sanctuaries.” [Online]. Available: https://sanctuaries.noaa.gov/visit/ecosystems/kelpdesc.html. [Accessed: 09-Jul-2018].

[237] “Bull Kelp · University of Puget Sound.” [Online]. Available: https://www.pugetsound.edu/academics/academic-resources/slater-museum/exhibits/marine-panel/bull-kelp/. [Accessed: 09-Jul-2018].

[238] “Bull kelp, Kelp Forest, Plants & Algae, Nereocystis luetkeana at the Monterey Bay Aquarium.” [Online]. Available: https://www.montereybayaquarium.org/animal-guide/plants-and-algae/bull-kelp. [Accessed: 09-Jul-2018].

[239] J. H. Rosman, S. G. Monismith, M. W. Denny, and J. R. Koseff, “Currents and turbulence within a kelp forest (Macrocystis pyrifera): Insights from a dynamically scaled laboratory model,” *Limnology and Oceanography*, vol. 55, no. 3, pp. 1145–1158.

[240] I. mindcomet com MindComet, “Adaptations.” [Online]. Available: https://seaworld.org/en/animal-info/animal-infobooks/killer-whale/adaptations. [Accessed: 02-Jul-2018].

[241] “Density of Seawater - The Physics Factbook.” [Online]. Available: https://hypertextbook.com/facts/2002/EdwardLaValley.shtml. [Accessed: 02-Jul-2018].

[242] “earth :: a global map of wind, weather, and ocean conditions.” [Online]. Available: https://earth.nullschool.net. [Accessed: 02-Jul-2018].

[243] “Ocean salinity,” *Science Learning Hub*. [Online]. Available: https://www.sciencelearn.org.nz/resources/686-ocean-salinity. [Accessed: 02-Jul-2018].

[244] “Florida Barometric Pressure Map - Air Sports Net.” [Online]. Available: http://www.usairnet.com/weather/maps/current/florida/barometric-pressure/. [Accessed: 02-Jul-2018].

[245] N. N. C. for E. I. US Department of Commerce, “Coastal Water Temperature Guide.” [Online]. Available: https://www.nodc.noaa.gov/dsdt/cwtg/egof.html. [Accessed: 02-Jul-2018].

[246] “Native Flora & Fauna :: Florida Museum of Natural History.” [Online]. Available: https://www.floridamuseum.ufl.edu/southflorida/habitats/estuarine-marine/flora-fauna/. [Accessed: 02-Jul-2018].

[247] “Catoctin Mountain Park Wind Forecast, MD - WillyWeather.” [Online]. Available: https://wind.willyweather.com/md/frederick-county/catoctin-mountain-park.html. [Accessed: 02-Jul-2018].

[248] J. E. Thomas *et al.*, “Catoctin Mountain Park Natural Resource Condition Assessment—SUMMARY,” p. 12.

[249] “Basic Information - Catoctin Mountain Park (U.S. National Park Service).” [Online]. Available: https://www.nps.gov/cato/planyourvisit/basicinfo.htm. [Accessed: 02-Jul-2018].

[250] “Specific Conductance in Streams,” p. 2.

[251] “American basswood | The Morton Arboretum.” [Online]. Available: http://www.mortonarb.org/trees-plants/tree-plant-descriptions/american-basswood. [Accessed: 02-Jul-2018].

[252] “Inventory & Monitoring at Catoctin Mountain Park (U.S. National Park Service).” [Online]. Available: https://www.nps.gov/im/ncrn/cato.htm. [Accessed: 02-Jul-2018].

[253] M. A. 6602 F. R. Thurmont and M. 21788 P.-9388 C. Us, “Trees and Shrubs - Catoctin Mountain Park (U.S. National Park Service).” [Online]. Available: https://www.nps.gov/cato/learn/nature/treesandshrubs.htm. [Accessed: 10-Jul-2018].

Appendices

Appendix A ASMA Matlab Code

```
% All Test

clc
clf
clear

%Environments by number
% Canyon = 1
% Polar Ocean = 2
% Reef = 3
% Tiaga = 4
% Kelp Forest = 5
% Deep Open Ocean = 6

enum=2;
r=FitFact(enum);
Totals=MobChar(enum);
T=Totals;
Fval=r.*T;
Final_Value = Fval'/max(Fval);
fprintf('\n')
fprintf('Final Value: %0.5f\n',Final_Value)
fprintf('\n')
R=EnviCorrCo(enum);


function [ r ] = EnviCorrCo( enum )
Range='B4:I5';
TestEnvi=xlsread('Environment.xlsx',enum,Range); % read in upper and
lower bounds for Cave
N=6;
m=100;
n=100000; % number of random samples
randnum=rand(1,n);

for h=1:N
Environment=xlsread('Environment.xlsx',h,Range); % read in upper and
lower bounds for Forest


p=length(TestEnvi(1,:));
q=length(Environment(1,:));
E1=zeros(n,p);
E2=zeros(n,q);
rsum=0;

for k=1:m
    for j=1:n
```

```
        for i=1:p
            a=TestEnvi(1,i);
            b=TestEnvi(2,i);
            E1(j,i)=(b-a)*abs(randnum(j))+a; % generate random values
within range for animal
        end
    end

    for j=1:n
        for i=1:q
            a=Environment(1,i);
            b=Environment(2,i);
            E2(j,i)=(b-a)*abs(randnum(j))+a; % generate random values
within range for environment
        end
    end

    rsum=rsum+abs(corr2(E1,E2));
end
r=rsum/m; % Average Correlation Coefficient
fprintf('Environment Correlation = %0.3f\n',r)
end
end


function [ r ] = FitFact( enum )
d=7;
rval=zeros(1,d);

for c=1:d
Animal=xlsread('Animals.xlsx',c,'B3:K4'); % read in upper and lower
bounds for animal
Environment=xlsread('Environment.xlsx',enum,'B4:I5'); % read in upper and
lower bounds for environment

m=100;
n=10000; % number of random samples
p=length(Animal(1,:));
q=length(Environment(1,:));
A=zeros(n,p);
E=zeros(n,q);
Rsum=zeros(p,q);

for k=1:m
    for j=1:n
        for i=1:p
            a=Animal(1,i);
            b=Animal(2,i);
            A(j,i)=(b-a)*abs(randn(1))+a; % generate random values within
range for animal
        end
```

```
    end

    for j=1:n
        for i=1:q
            a=Environment(1,i);
            b=Environment(2,i);
            E(j,i)=(b-a)*abs(randn(1))+a; % generate random values within
range for environment
        end
    end

    Rsum=Rsum+abs(corr(A,E));
end

R=Rsum/m; % Average Correlation Matrix

O1=Animal(1,:);
O2=Animal(2,:);
F1=Environment(1,:);
F2=Environment(2,:);
rlow=O1*R*F1'; % Lower Bound Fitness Factor
rhigh=O2*R*F2'; % Upper Bound Fitness Factor
rval(c)=(rlow+rhigh)/2; % Average Fitness Factor

end

r=rval;
fprintf('Fitness Score: %0.3f\n',r)
end


function [ Totals ] = MobChar( enum )
k=7;
avg=zeros(k,6);
names=['Owl        ';'Eagle      ';'Orca       ';'Penguin    ';'Frigate
';'Seal       ';'Stingray   ']
%%
for j=1:k
m=100000;
Aval=xlsread('Animals.xlsx',j,'B3:K4');
Eval=xlsread('Environment.xlsx',enum,'B4:I5');
A=zeros(length(Aval(1,:)),m);
E=zeros(length(Eval(1,:)),m);
M=zeros(6,m);

fprintf('\n')
fprintf('Animal # %0.0f\n',j)
%Producing 100000 samples between the given bounds within the Animal and
%Envrionment xlsx sheets
for i=1:length(Aval(1,:))
```

```
    A(i,:)=(Aval(2,i)-Aval(1,i))*abs(randn(m,1))+Aval(1,i);
end

for i=1:length(Eval(1,:))
    E(i,:)=(Eval(2,i)-Eval(1,i))*abs(randn(m,1))+Eval(1,i);
end

% Animal Specifications
l=A(1,:); % Length
w=A(2,:); % Width
b=A(3,:); % Wingspan
W=A(4,:); % Weight
DF=A(5,:); % Degrees of Freedom
R=A(6,:); % Range
P=A(7,:); % Power
V=A(8,:); % Velocity
a=A(9,:); % Acceleration
S=A(10,:);% Wing Area

% Environment Specifications
OD=E(1,:); % Obstacle Density
OH=E(2,:); % Obstacle Height
OW=E(3,:); % Obstacle Width
SL=E(4,:); % Salinity Level
T=E(5,:); % Pressure
p=E(6,:); % Fluid Speed
Pr=E(7,:); % Pressure
u=E(8,:); % Fluid Speed
g=9.81; % Gravitational Acceleration

% Lift
CL=1.5; % Coefficient of Lift (Assumed low Reynolds Number)
AR=b.^2./S; % Aspect Ratio
% Oswalt Efficiency Factor (Assumed based on Reynolds Number) Create
average between 0.85 and 0.99
erange=(0.99-0.85)*abs(rand(10000,1))+0.85;
e=mean(erange);
L=0.5.*p.*(V+u).^2.*S.*CL; % Lift Force

% Drag
CDOrange=(0.07-0.01)*abs(rand(10000,1))+0.01; % Average between 0.01 and
0.07
CDO=mean(CDOrange);
CD=CDO+CL.^2./(pi.*e.*AR);
D=0.5.*p.*(V+u).^2.*S.*CD; % Drag Force
%%
%Calculating Mobility Char.
% Hover/
M(1,:)=L; % Force Required to Remain at given Height Location
(Assumption)
```

```
% Glide
M(2,:)=atan(CD./CL).*180./pi; % Glide Angle in Degrees

% Dive
M(3,:)=sqrt(2.*W./(CDO.*p.*S)); % Terminal Velocity

% Soar
M(4,:)=W./S; % Wing Loading

CLRC=(W./S)./(0.5.*p.*(V+u).^2);
CDRC=CDO+CLRC.^2./(pi.*e.*AR);
PRRC=(W./(CLRC./CDRC)).*(V+u);

M(5,:)=abs((P-PRRC)./W); % Rate of Climb

% Flapping/Swimming
M(6,:)=W.*a+D; % Thrust Force

Mnames=['Lift             ';'Glide Angle      ';'Terminal Velocity';'Wing
Loading     ';'Rate of Climb    ';'Thrust           '];

% for AN = 1:length(k);
    figure
for i=1:6
    fprintf('Mobility Characteristic: ')
    disp(Mnames(i,:));
    %subplot(6,k,j+k*(i-1))
    subplot(2,3,i)
    %hold on
%     figure
    titlename=['Animal # ',num2str(j),' Characteristic # ',num2str(i)];
    title(titlename);
    %histogram(M(i,:), 100) can be used but does not have normal curve
    %overlay
    fitdist(M(i,:)','kernel'); % 95% Confidence Interval also gives curve
data including max, min, mu, and sigma
    histfit(M(i,:)',50,'kernel');%histfit displays a histogram of the
data and overlays a normal fit curve over the histogram, number of bins
equal to sqrt(number of elements)
    minv=min(M(i,:));
    maxv=max(M(i,:));
    fprintf(' Minimum Value = %0.3f\n',minv);
    fprintf(' Maximum Value = %0.3f\n',maxv);
    avg(j,i)=mean(M(i,:));
end
% end

Totals=0;
fprintf('\n')
for i=1:6
    fprintf('\n')
```

```
    if i==2
            fprintf('Ranking for ');
            disp(Mnames(i,:));
            [~,An]=sort(avg(:,i));
            for j=1:length(An)
                Rank=names(An(j),:);
                disp(Rank);
            end
    else
            fprintf('Ranking for ');
            disp(Mnames(i,:));
            [~,An]=sort(-avg(:,i));
            for j=1:length(An);
                Rank=names(An(j),:);
                disp(Rank)
            end
    end
    Totals=Totals+An;
end

fprintf('\n')
fprintf('Total Ranking Sums\n')
for i=1:k
    disp(names(i,:));
    fprintf(' %0.0f\n',Totals(i))
end



end
```

Appendix B Animal Specifications

Animal Specifications: Lower and Upper Bounds

Owl (Great Horned: Bubo virginianus)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.4572	0.2587	1.00584	1.49685	2	0.316	0	0	0	0.0524
Upper Bound:	0.546	0.309	1.46304	2.49476	11	1.732	1	22.2	1	1.248

Figure 51: Owl Eagle Animal Specification Bounds [181]–[184]

Eagle (Golden: Aquila Chrysaetos)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.8382	0.2935	1.8288	2.72155	2	11.61	0	0	0	0.3368
Upper Bound:	0.9652	0.338	2.286	6.80389	11	48.98	**1**	88.9	**1**	0.5422

Figure 52: Eagle Animal Specification Bounds [185], [186]

Appendix B
Animal Specifications: Lower and Upper Bounds

Whale (Orca: Orcinus orca)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	7.0104	1.655	4.729	1300	3	0	0	0	0	1.2434
Upper Bound:	9.7536	2.303	6.58	5443	4	800	36300	12.5	13.72	2.407

Figure 53: Orca Animal Specification Bounds [187], [188]

Penguin (Gentoo: Pygoscelis papua)										
Animal Specifications:	Length (m)	Width (m)	Wing/Fin Span (m)	Weight (kg)	DoF	Range (km)	Power (W)	Velocity (m/s)	Acceleration (m/s^2)	Wing Area
Lower Bound:	0.7	0.223	0.398	5	2	0	0	0	0	0.0026
Upper Bound:	0.95	0.302	0.54	8	6	25.7495	87.7	9.8	1	0.0048

Figure 54: Penguin Animal Specification Bounds [189], [190]

Appendix B
Animal Specifications: Lower and Upper Bounds

Frigate Bird (Magnificent: Fregata magnificens)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.89	0.113	2.17	1	2	0	0	0	0	**0.1974**
Upper Bound:	1.45	0.164	2.2	1.9	4	1000	1	42.5	1	**0.2014**

Figure 55: Frigate Animal Specification Bounds [191], [192]

Seal (Harp: Pagophilus groenlandica)										
Animal Specifications:	Length (m)	Width (m)	Wing/Fin Span (m)	Weight (kg)	DoF	Range (km)	Power (W)	Velocity (m/s)	Acceleration (m/s^2)	Wing Area
Lower Bound:	1.6	0.532	0.7111	120	3	0	0	0	0	0.0032
Upper Bound:	1.8	0.598	1.28	180	36	2.3885	15299	8.06	10.3	0.0466

Figure 56: Harp Seal Animal Specification Bounds [193]–[196]

Appendix B
Animal Specifications: Lower and Upper Bounds

Stingray										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.9	0.16	0.48	78.4	0	0	0	0	0	3
Upper Bound:	1.5	0.267	0.8	97	1	0.207	44678	48.28	34.3	5.0266

Figure 57: Sting Ray Animal Specification Bounds [197]–[199]

Falcon: Peregrine (Falco peregrinus)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	Wing Area
Lower Bound:	0.36	0.09	1	0.5	2	0	0	0	0	
Upper Bound:	0.49	0.123	1.1	2	11	5	14.774	157	11.5	

Figure 58: Peregrine Falcon Animal Specification Bounds [157], [200]–[203]

Appendix B
Animal Specifications: Lower and Upper Bounds

Sea Turtle (Green: Chelonia mydas)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.787	0.394	0.787	68	3	3.95	0	0	0	
Upper Bound:	1.19	0.595	1.19	181	27	18.5	220	2	1.0567	

Figure 59: Sea Turtle Animal Specification Bounds [204]–[206]

Sea Lion (Steller: Eumetopias jubatus)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	2.362	0.394	0.091	350	3	0	0	0	0	0.01
Upper Bound:	3.25	0.542	0.125	1120	36	900		7.5	5.5	0.0192

Figure 60: Seal Lion Animal Specification Bounds [207]–[209]

Appendix B

Animal Specifications: Lower and Upper Bounds

Bat (Lesser long-nosed: Leptonycteris yerbabuenae)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.06985	0.015	0.326	0.0185	3	0	**0**	0	0	0.01
Upper Bound:	0.0762	0.016	0.356	0.023	31	50	0.463	7		0.012

Figure 61: Bat Animal Specification Bounds [210], [211]

Hawk (Northern Goshawk: Accipiter gentilis atricapillus)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	0.55	0.115	0.98	0.631	2	0	0	0	0	0.104
Upper Bound:	0.61	0.127	1.15	1.364	11	6.356		55 m/s		0.1454

Figure 62: Hawk Animal Specification Bounds [212], [213]

Appendix B
Animal Specifications: Lower and Upper Bounds

Manatee (Trichechus manatus)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:					3		0	0	0	
Upper Bound:	3.2	0.851		395	33		149	6.705		

Figure 63: Manatee Animal Specification Bounds [214]–[216]

Walrus (Pacific: Odobenus rosmarus divergens)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	2.3			400	2					
Upper Bound:	3.6			1700	21			9.72		

Figure 64: Walrus Animal Specification Bounds [217]

Appendix B
Animal Specifications: Lower and Upper Bounds

Shark (Short-finned Mako: Isurus oxyrinchus)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	3.2			60			0	0	0	
Upper Bound:	3.8	0.46	1.7	500				22.22		

Figure 65: Shark Animal Specification Bounds [218], [219]

Otter (Sea: Enhydra lutris kenyoni)										
Animal Specifications:	**Length (m)**	**Width (m)**	**Wing/Fin Span (m)**	**Weight (kg)**	**DoF**	**Range (km)**	**Power (W)**	**Velocity (m/s)**	**Acceleration (m/s^2)**	**Wing Area**
Lower Bound:	1			16	3		0	0	0	
Upper Bound:	1.5			39	36			.416		

Figure 66: Otter Animal Specification Bounds [220]–[222]

Appendix C Environmental Specifications

Environmental Specifications: Lower and Upper Bounds

Canyon								
Environmental Specifications:	**Density of Obstacles**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	0	0	420	-1	0.9	100.85	0
Upper Bound:	500	1600	500	1022	17	1.2	102	8.33

Figure 67: Canyon Environmental Specification Bounds [223]–[225]

Polar Ocean								
Environmental Specifications:	**Density of Obstacles**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	0	0	0.0355	0	1.0245	0.0972	0.0217
Upper Bound:	20	20	20	0.3468	35	1.029	2.7446	0.8103

Figure 68: Polar Ocean Environmental Specification Bounds [226]–[228]

Appendix C

Environmental Specifications: Lower and Upper Bounds

Reef								
Environmental Specifications:	**Density of Obstacles**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	1	1	32	10	1026	980066	0.2
Upper Bound:	20	7	7	40	30	1027	980066.5	1.2

Figure 69: Reef Environmental Specification Bounds [228]–[232]

Taiga								
Environmental Specifications:	**Density of Obstacles (stems/ha)**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	0	0	0	-53.889	1.2	61.595	0
Upper Bound:	2650	1.828	1.828	1	21.111	1.611	91.021	17

Figure 70: Taiga Environmental Specification Bounds [127], [233]–[235]

Appendix C
Environmental Specifications: Lower and Upper Bounds

Kelp Forest								
Environmental Specifications:	**Density of Obstacles (Stems/ha)**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	5	0	0.000	5	998.234	121.429	0
Upper Bound:	9300	20	0.1	0.000	20	999.992	402.879	0.3

Figure 71: Kelp Forest Environmental Specification Bounds [236]–[239]

Deep Ocean								
Environmental Specifications:	**Density of Obstacles**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	0	0	34	-1.8	1020	500	0.1
Upper Bound:	0.01	0.01	0.01	37	30	1030	2611.81	2.26

Figure 72: Deep Ocean Environmental Specification Bounds [240]–[243]

Appendix C
Environmental Specifications: Lower and Upper Bounds

Estuaries								
Environmental Specifications:	**Density of Obstacles**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	0	0	0	21.66		100.98	0.05
Upper Bound:	40	0.914	10	35	32.22	21.75	101.39	0.85

Figure 73: Estuaries Environmental Specification Bounds [242], [244]–[246]

Deciduous Forest								
Environmental Specifications:	**Density of Obstacles**	**Height (y) Obstacles (m)**	**Width (x) Obstacles (m)**	**Salinity Level (g/cubic meter)**	**Temperature degree C**	**Density of Fluid (Kg/m^3)**	**Pressure (kPa)**	**Fluid Speed (m/s)**
Lower Bound:	0	0	0.1524	100	5	1.1845	94.66	0
Upper Bound:	38.3	24.38	0.6096	150	28	1.2396	99.06	5

Figure 74: Deciduous Forest Environment Specification Bounds [247]–[253]