Classification of Flapping Wing Mechanisms for Micro Air Vehicles

Conference Paper · August 2012

DOI: 10.1115/DETC2012-70953

2 authors:

Mark Ryan
Milwaukee School of Engineering

Hai-Jun Su
The Ohio State University

Proceedings of the ASME 2012 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2012
August 12-15, 2012, Chicago, IL, USA

DETC2012-70953

CLASSIFICATION OF FLAPPING WING MECHANISMS FOR MICRO AIR VEHICLES

Mark Ryan, Hai-Jun Su *
Department of Mechanical and Aerospace Engineering
The Ohio State University
Columbus, Ohio 43210

ABSTRACT

The purpose of this paper is to categorize the current state of technology in flapping wing mechanisms of micro air vehicles (MAVs). One of the major components of MAVs is the flapping mechanism, which actuates wings to generate sufficient lift and propulsion force. The goal of the flapping wing mechanism design is to develop a highly efficient and highly robust mechanism, which converts the input motion, either rotational or translational, to a beating motion at a frequency ranging from several to hundreds of Hz. The current practice of designing flapping mechanisms follows an ad-hoc approach with multiple design, build, and test cycles. This design process is very inefficient, costly, time-consuming, and not applicable to mass production of MAVs. This work will be an important step towards a systematic approach for the design of flapping mechanisms for MAVs. In this paper, we will study 15 flapping mechanisms used in recent MAV projects worldwide. We classify these mechanisms based on workspace, compliant or rigid body, type synthesis, mobility, and actuator type. This survey of mechanism classification will serve as a resource for the continued design and development of smaller and more efficient MAVs.

1 Introduction

1.1 Background

The Defense Advanced Research Projects Agency (DARPA) defined a MAV [1] as a small size ($<$ 15cm) autonomous flying craft, which takes advantage of increasingly miniaturized electro-mechanical technologies. In recent years, academia and the Department of Defense (DoD) labs have been devoting more and more resources to MAV research.

However, the major challenges of scaling down MAVs continue to be decreased efficiency at smaller sizes [2]. This includes the decreased aerodynamic efficiencies at lower Reynolds numbers, and decreased power transmission in traditional flapping mechanisms. To counter act the decreasing aerodynamic efficiency, higher frequency flapping is required, which in turn requires an increase in the power to weight ratio; however, the currently available power sources and actuators dominate the overall weight of present MAVs. Furthermore, manufacturing and assembly techniques become more challenging as progressively smaller scales are pursued.

The major components of a MAV include the power source, actuators, control system, transmission, wings, and supporting structure. The focus of this paper is the transmission, which is functionally responsible for the conversion of power into the desired maneuvering tasks, through the appropriate aerodynamic considerations. Design requirements for the flapping mechanism include wing kinematics, actuator type, flapping frequency, power efficiency, elastic storage, control, weight, cost, material selection, manufacturing process, scalability, and assembly.

In terms of aerodynamic performance, lift is generated primarily through leading edge vortices (LEV) and wing rotational forces [3]. Several parameters can be adjusted to achieve specific flight tasks, which have been modeled mathematically. Many MAV designs have used nature for inspiration in their design process. The insect's thorax is a resonate driven structure, which can be modeled as a four-bar linkage. Through the use of direct and indirect muscles, insects manipulate the shape of their thorax to drive their wings [4, 5]. Using nature as a source of inspiration, research institutions worldwide have developed several different types of mechanisms capable of producing the required kinematics and lift force for sustaining flight.

1.2 Research Organizations

In this paper, we investigate the current state of technology in flapping wing mechanisms through a literature survey. The

*address all correspondence to this author, Email: su.298@osu.edu.

MAV projects captured in this survey are from a variety of research institutes and industry worldwide. Table 1, 2, and 3 summarize these flapping wing mechanism designs by the major research group. A brief description of these research groups is given below.

AeroVironment specializes in the design and development of unmanned aircraft systems (UAS), and electric energy technologies, which include electric motors, energy storage, power electronics, and controls. As part of DARPA's Nano Air Vehicle (NAV) program, AeroVironment developed the Nano Hummingbird [6]. This fully autonomous air vehicle demonstrates the ability to perform controlled hovering flight with only the use of its two flapping wings. Previous work on MAVs included a collaboration with the California Institute of Technology and the University of California, Los Angles (UCLA), to develop the MicroBat MAV [7].

Berkeley and Harvard have collaborated on the Micromechanical Flying Insect (MFI) [8] and the Harvard Microrobotic Fly (HMF) [9], respectively. These insect sized MAVs utilize Bimorph Piezoelectric actuators and Smart Composite Microstructures (SCM), a meso-scale manufacturing process for compliant mechanisms. In particular, researchers at Berkeley have developed unique wing differentials to actively control the wing trajectory [10, 11]. The MFI transmission and coupled wing differentials will be examined in detail. Harvard has expanded on the HMF concept and developed the recent Passive Aeromechanical Regulation of Imbalanced Torques (PARITy) transmission [12, 13]. Instead of actively controlling the wing trajectory, this drive train has an additional degree of freedom (DOF), which passively balances the applied aerodynamic loading.

The Warsaw University of Technology and Cranfield University has pursued the development of insect-like wing kinematics, using rigorous mechanism design as in [14–16]. Propeller, fixed-wing, and flapping wing MAV platforms have been compared in great detail in [17]. In addition, non-linear unsteady aerodynamic models have been developed to aid in the design process [18, 19]. The design examined in this survey is a double scotch yoke mechanism, which has been named the Lissajous MAV for this survey. The Liassajous curves are a specific set of mathematical equations, which are a composition of two sinusoidal waveforms in orthogonal directions, which produce the desired figure-of-eight/banana shape wing trajectory.

India's Defense Research and Development Organization (DRDO) [20] has developed a flapping biomimetic mechanism, which is capable of vertical take-off and landing (VTOL MAV). Active flight control, which allows multi-mode flight or different flapping patterns, has been incorporated in their designs through adjustable parameters in the mechanism. The DRDO has also developed two different types of steering mechanisms, which are based on differential steering and steering by altering the center of gravity [21].

The University of Delaware has developed a number of MAVs, with a focus on energy storage and resonant drive technology. Their development process includes: trajectory planning, dynamic analysis, aerodynamic analysis, optimization, simulation, sensory, and controls. Discussed in this survey is their Flapping Wing Micro Air Vehicle (FWMAV) [22], which exhibits elastic storage and resonant drive, to improve the efficiency of the transmission. The focus of this design is to store kinetic energy and release it during subsequent strokes.

A progressive series of scaled down MAVs have been developed by Delft University [23–25]. The goal of this program has been to develop fully autonomous systems with on-board cameras and transmitters , and to continually miniaturize the design. In addition, an autonomous vision-based flight control system is being investigated, where the measured flow from the camera is coupled to the internal steering commands. The progression of the DelFly I, II, and modified II transmissions will be examined.

The Artificial Muscle Lab at Konkuk University has developed the Lightweight Piezoelectric (PZT) Composite Actuator (LIPCA) [26], which was fabricated with layers of carbon fiber/epoxy, PZTs, and glass/epoxy. Researchers at Konkuk have focused on many different types of linear actuators, but have also implemented several DC motors into their MAVs for flight competitions. Several types of MAVs have been developed, which include successfully smaller scale designs. The MAV discussed in this survey is powered by LIPCA and features a four-bar linkage for mechanical amplification of the actuator.

The University of Maryland has developed an integrated product design process [27], which focuses on the use of parametric optimization, design for injection molding, and multimaterial injection molding (MMM) [28]. The Small Bird and Jumbo Bird MAVs are examined in this paper for their use of flexural members and flexural joints. The integration of compliant mechanisms and injection molding offer many benefits, which will be discussed.

1.3 Motivation

Even though research has produced a vast collection of flapping wing mechanisms, the design process is still a very challenging task. The typical design practice is an ad-hoc approach with multiple design, prototype build, and test cycles. This design process is very in-efficient, costly, and time-consuming. A recent example is the design of AeroVironment's Nano Hummingbird project, which took more than five years and four million US dollars [29]. There is no evidence showing that this process is repeatable and applicable to massive production of MAVs. Since the design of flapping wing mechanisms requires a significant portion of the overall efforts, it is important to develop a systematic approach, which is scalable to MAVs of different sizes.

As the first step working towards this goal, in this paper, we will apply a classification technique to categorize the flapping wing mechanisms using five criteria: 1. Workspace: Planar, Spherical, or Spatial, 2. Rigid Body or Compliant Mechanism, 3. Type Synthesis of Mechanism, 4. Mobility, and 5. Actuator Type. This classification of mechanisms is intended to provide the designer with a tool for assessing design alternatives and documenting the advancements in flapping type synthesis.

2 Methodology

In this section, we will review the methodology to be used in categorizing the flapping wing mechanisms.

2.1 Mechanism Workspace

The workspace of a mechanism is defined as the set of positions that a workpiece can reach. The workpiece of a MAV is the wing, and the workspace is the generated wing trajectory. The flapping stroke is the primary component required for generating sufficient lift force. However, the pitching motion or the rolling of wings is also very important for modulating the angle of attack. Berman and Wang [30] have studied the flapping kinematics of insects, and created the following mathematical models. The flapping angle $\phi(t)$, the heave angle $\theta(t)$ and pitching angle $\eta(t)$ of insects are given by

$$\phi(t) = \frac{\phi_m}{\sin^{-1} K} \sin^{-1}[K \sin(2\pi f t)], \tag{1}$$
$$\theta(t) = \theta_m \cos(2\pi N f t \Phi_\theta) + \theta_0, \tag{2}$$
$$\eta(t) = \frac{\eta_m}{\tanh C_\eta} \tanh[C_\eta \sin(2\pi f t + \Phi_\eta)] + \eta_0, \tag{3}$$

where the kinematics parameters such as ϕ_m are observed directly from insect flight. From this mathematical model, Figure 1 exhibits the flapping motion of a Bumblebee. The trajectory of the wing is approximately a spherically based figure-of-eight banana shape, where the leading edge of the wing is represented with an arrow. The insect kinematics from this study will give us a specific design goal of flapping mechanism.

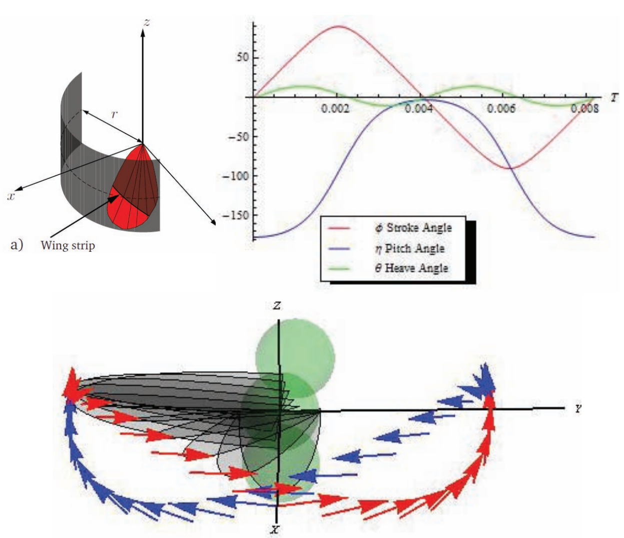


Figure 1. The flapping kinematics of Bumblebees. Top left: a typical flapping wing. Top right: plot of kinematic parameters. Bottom: trajectory of the wing tip.

The flapping drive mechanisms are classified as planar, spherical, or spatial. The components of a planar mechanism all move in parallel planes, and utilize lower-pair joints. Theoretically, the planar joint axes intersect at infinity. A spherical mechanism generates spherically concentric motion about the spherical center of the mechanism. All the joint axes must intersect at the spherical center point. Any mechanism which cannot be classified as planar or spherical is a spatial mechanism. However, planar and spherical mechanisms may be considered special cases of spatial mechanisms, due to unique geometry and the orientations of their joint axes.

2.2 Rigid body vs. Compliant Mechanisms

Currently, most flapping transmissions are considered rigid body mechanisms, i.e. linkages are considered infinitely rigid. The motion of rigid body mechanisms is typically more intuitive, more controllable, and exhibits a large range of motion. In addition, rigid body mechanisms generally have high force and energy conversion efficiency. However, as mechanisms are scaled down, energy losses due to joint friction cannot be recovered, especially when bearing surfaces are not feasible. As mentioned previously, manufacturing and assembly techniques become more challenging at smaller scales, and errors may affect the performance of the final design. For these reasons, rigid body mechanisms are often seen in bird-sized MAVs such as the University of Delft's Delfly I, DRDO's VTOL MAV, and Konkuk University's LIPCA MAV.

For micro or nano MAVs, low friction pin joints with ball bearings are not feasible. Hence, mechanisms with flexural joints or "compliant mechanisms" [31] become a more natural solution. There are several examples of applying compliant mechanisms to flapping wing MAVs. A compliant mechanism deforms when loaded, and transforms motion and forces through the deflection of their flexible members. The advantages of compliant mechanisms includes no binding (monolithic design), concise design (flexible members serving multiple functions), light (reduced part count), low maintenance (no bearing, no lubrication), and high precision (no backlash or wear). These benefits make compliant mechanisms an excellent choice for addressing the challenges in the design of MAVs. Figure 2 depicts a rigid body four-bar linkage and a compliant four-bar linkage.

Even though compliant mechanisms exhibit many benefits, caution must be practiced especially in the application of MAVs. Fatigue is a primary concern due to the relatively high flapping frequency, which is required to combat the unsteady aerodynamics that are present in smaller scale MAVs. Another possible disadvantage may be the reduced range of motion, i.e. a compliant input crank cannot produce a continuous rotational motion. Historically, it has been more challenging to design compliant mechanisms; however, much advancement has been made to simplify this process, such as pseudo-rigid body analysis [31].

There are three types of compliant mechanisms, which will be considered during this classification: compliant or flexural joints, short compliant segments, and long compliant segments. Flexural joints localize the compliance in the mechanism, and typically allow small deflections. Flexural members distribute compliance in a mechanism to enhance the desired transformation of motion and forces. Short compliant segments exhibit relatively small deflection, when compared to the large and possibly non-linear deflections of long compliant segments.

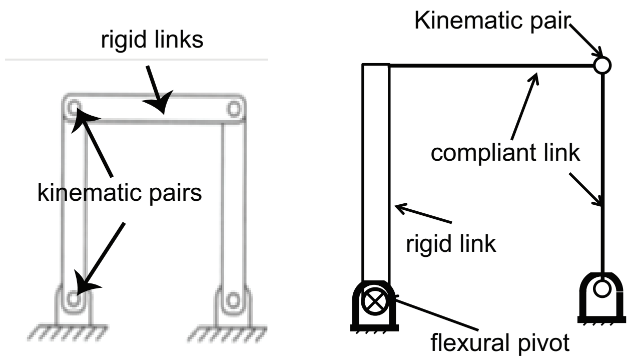


Figure 2. Rigid body four-bar linkage (left) vs. compliant four-bar linkage (right).

2.3 Type Synthesis of Mechanisms

Tsai [32] has systematically classified planar and spatial mechanisms by using a graph theory. Each mechanism may be represented by a graph expressed in a so called "adjacency matrix." Murphy [33] has extended this type synthesis to compliant mechanisms by using a similar approach. In contrast to a rigid body mechanism, each link of a compliant mechanism may be classified as rigid, compliant, or ground link. The connection types in a compliant mechanism are: kinematic pair, flexural pivot, or clamped joint. A compliant mechanism may be represented by the so called "compliant mechanism matrix".

The adjacency matrix is a $(n \times n)$ square matrix, where n denotes the number of links or segments in the mechanism. For a given mechanism, the diagonal elements of the matrix denote the segment type, and the off-diagonal elements denote the connection types between the segments. The segment types of ground, rigid body, and compliant members are represented with a -1, 0, and 1, respectively. The connection types are as follows: no connection is 0, lower kinematic pair is 1, flexural pivot is 2, clamped connection is 3, gear pair is 4, pulley pair is 5, universal joint is 6, and scotch yoke is 7. The composition of the adjacency matrix is summarized in Figure 3. The main focus of the adjacency matrix is to capture the driving mechanism of the MAV. To allow for universal comparisons between MAV transmissions, only the simplest form of the mechanism which enables flapping motion will be analyzed using type synthesis. For example Berkeley's MFI has four equivalent linkage mechanisms to ensure stability, type synthesis of one of these mechanisms is sufficient. If the micro air vehicle had a relatively simple passive wing rotation joint it was noted and not included in the adjacency matrix. However, if the wing rotation mechanism exceed a lower kinematic pair, then a separate adjacency matrix was developed, i.e. Berkeley's Wing Differential I .

Segment Type	
Ground	-1
Rigid Body	0
Compliant	1
Gear	G
Cable	C
Yoke	Y

Connection Type	
None	0
Lower Kinematic Pair	1
Flexural Pivot	2
Clamped	3
Gear Pair	4
Pulley Pair	5
Universal Joint	6
Scotch Yoke	7

Figure 3. Definition of segment types and connection types

$$[A] = \begin{bmatrix} -1 & 1 & 0 & 1 & 0 & 2 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 & 0 & 2 \\ 2 & 0 & 0 & 0 & 2 & 0 \end{bmatrix} \tag{4}$$

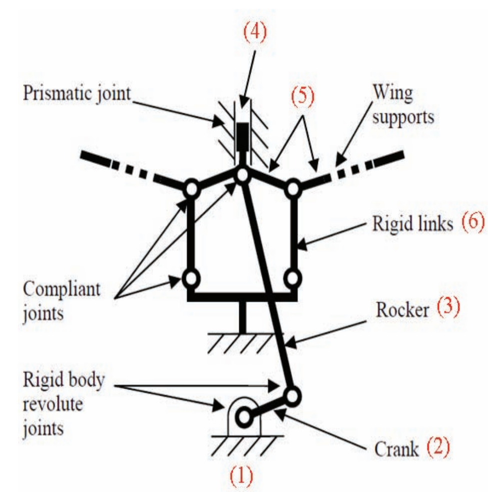


Figure 4. The flapping mechanism used in University of Maryland's Jumbo Bird design. The number are the indices of links.

To demonstrate the adjacency matrix, let us study the flapping mechanism used in University of Maryland's Jumbo Bird design (Figure 4). Only half of this mechanism will be considered in the adjacency matrix, as this is a symmetric design. To construct the adjacency matrix, we first number the links of the mechanism. For instance, the ground link is labeled as "1" and right wing is labeled as "5". The diagonal elements represent the type of links. For this example, since all links are rigid and link

1 is the ground link, all the diagonal elements are zeros except the first one being "-1". To construct each row of the matrix, we consider a link and study the connectivity of this with other links. For instance, the ground link is connected to links 2 and 4 with revolute and prismatic joints, and to links 6 by a flexure joint. By repeating this process for each link, we can obtain the adjacency matrix for this mechanism, as seen in Figure 4.

Once the adjacency matrices have been created, a systematic technique for detecting isomorphism is applied. If two mechanisms have one-to-one correspondence in their topology, then the mechanisms are isomorphic [32]. Since numbering methods in the creation of adjacency matrices may differ for a group of mechanisms, a systematic approach is used. A characteristic polynomial is calculated for each adjacency matrix, and the resulting coefficients are compared to detect isomorphism. The characteristic polynomial (CP) is calculated as follows:

$$CP = |xI - A|, \tag{5}$$

where x is the variable, I is an identity matrix of order n, and A is the adjacency matrix of the mechanism. This detection of isomorphism allows the designer to recognize equivalent mechanisms during the initial design phases, especially when considering a large database of existing designs. Continuing the type synthesis example of Maryland's Jumbo Bird, the characteristic polynomial is calculated using (5):

$$CP = x^6 + x^5 - 16x^4 - 10x^3 + 32x^2 + 12x - 16 \tag{6}$$

2.4 Mobility

The motion of a mechanism is characterized by the pattern of interconnection of links called *kinematic structure* or *type* of the mechanism. The mobility or degree-of-freedom (DOF) of kinematic structure is given by the well known Grubler-Kutzbach criterion, expressed as:

$$M = \lambda(N - J - 1) + \sum_{i=1}^{J} f_i, \tag{7}$$

where N and J are the number of links and number of joints, respectively; f_i are the DOF ith joint. For planar and spherical topologies $\lambda = 3$ and for spatial topologies $\lambda = 6$. Overall, the range of mobility is $1 \leq M \leq \lambda$. By enumerating all permissible integer values of N and J in (7), one can obtain all combinations of kinematic structures.

As discussed in Section 2.1, an insect's wing kinematics is modeled mathematically in Eqs.(1-3). These represent the 3 DOF, which need to be considered in the flapping mechanism design. Adjusting these parameters will allow different flight modes and maneuvers such as forward flight and turning. Approximations of insect flight may be obtained with less degrees of freedom, and through the use of auxiliary systems or additional control surfaces, such as rudders or tails. For example, the Jumbo Bird MAV exhibits a planar flapping motion to produce lift, and a rudder based mechanism, which provides the MAV with the ability to make turns.

With the adjacency matrices developed, the mobility for each mechanism is readily calculated. In this survey, the primary focus is the transmission, and the mobility calculation reflects this. As mentioned previously, passive wing rotation joints of a lower kinematic pair have been noted, but not included in this calculation. If the wing rotation mechanism exceeded a lower kinematic pair, then a separate calculation was perform, i.e. Berkeley's Wing Differential I. Auxiliary systems which are separate from the primary transmission are not considered in this survey, i.e. tail/rudder mechanisms. A sample mobility calculation is given for the Jumbo Bird MAV:

$$M = 3(6 - 7 - 1) + (7)(1) = 1 \tag{8}$$

2.5 Actuator Type

Separate to the classification of MAV transmissions is the classification of actuators, and the development of a selection database [34]. Several families and sub-types have been identified and categorized by a number of characteristics which include: maximum output strain, maximum frequency, maximum energy density, efficiency, mass, volume, and many more. Some of the major classes of actuators are electromagnetic, electromechanical, fluidic, piezoelectric, smart materials, and hybrid. The selection of actuator, power source, control system, and transmission must be integrated, as there is an inherent relationship between them.

As part of the scalability of the MAV, the selection of actuator will affect the feasibility of the design. Scaling actuators from macro to micro will result in varying performance characteristics. In some cases, where a marco actuator type is readily available, there are challenges present in the manufacture and efficiency of the micro version. In regards to the scaling up of actuators from micro to macro, the underlying physics associated with the functioning of the actuator may not possible [35]. In this paper we will limit ourselves to the general categorization of the type of actuator as rotary and linear, and how this impacts the mechanism design. The details of actuator selection and performance are left to detailed resources.

In terms of transmission design, the rotary and linear actuators require fundamentally different intermediary mechanisms, to transform the given input motion into a reciprocating flapping motion. There are advantages and disadvantages associated with each type of mechanism. A major difference may be how adjustable the kinematics of mechanism is, as discussed in [3]. Adjustable kinematics is more attainable in mechanism with linear actuators. Additional DOF can be added to the transmission to allow the adjustment from one flight pattern to another. Rotary based mechanisms generally have a constrained output, which limits the wing trajectory to a single, fixed path.

3 Classification of Flapping Mechanisms

In this section, we classify flapping mechanisms by workspace, rigid body or compliant, type synthesis, mobility, and actuator type. All of these classifications, except type synthesis are summarized in Table 1. The kinematic diagrams, adjacency matrices, and characteristic polynomial coefficients are found in Table 2 and 3.

3.1 Workspace

In this survey, fifteen mechanisms have been classified as follows: ten planar, two spherical, and three spatial (Table 1). In general, planar mechanisms have the advantage of being easier to design, manufacture, and assemble. The major disadvantage of planar mechanisms for MAV is the ability to generate insect-like kinematics. Additional control surfaces, auxiliary mechanisms, and actuators will be required to produce a better approximation of insect-like flight. Examples of this are the DelFly I, New DelFly II, Small Bird, and Jumbo Bird MAVs, which feature planar transmissions and tail surfaces [36]. Spherical mechanisms (i.e. Lissajous MAV) are able to generate the figure-of-eight, banana-shape trajectory, which is shown in Figure 1. With this benefit may come the complication of manufacture and assembly, as all joint axes must intersect at the spherical center of the mechanism to avoid binding. While more realistic insect-flight patterns are possible, additional DOF translates directly into additional actuators and more weight. Spatial mechanisms like spherical mechanisms are able to generate the insect-like kinematics, but may offer more flexibility in terms of adjustable kinematic parameters (i.e. not limited to concentric spherical operation). An example of this is the VTOL MAV, which is able to generate four different flight patterns. When compared to the simplistic nature of planar mechanisms, the manufacture and assembly of spatial mechanisms is more challenging.

3.2 Rigid Body or Compliant Mechanisms

As part of this classification, the transmissions were sorted by segment type as follows: seven rigid body mechanisms, seven compliant joint mechanisms, one short compliant member mechanism, and no long compliant member mechanisms. It is interesting to note that only planar mechanisms feature compliant components; however, the MFI wing differentials do feature compliant joints. Of the compliant mechanisms, use of the flexural joints dominated, which may be due to their relatively easy analysis and fabrication. In Section 2.2, the advantages and disadvantages were discussed in detail.

The University of Maryland's Small Bird MAV demonstrates the ideal application of compliant mechanisms. The Small Bird uses flexural members to reduce the peak motor torque. The motor experiences peak torque at the beginning of the up-stroke and the down-stroke, due to the aerodynamic loading of the wings. When the crank and coupler reach over-center, the compliant frame reaches its maximum deflection. Once the crank pulls away from the maximum point, the compliant members release their stored energy, and assist the motor in overcoming the peak aerodynamic loading in the stroke cycle. The compliant frame was manufactured as a single piece, using injection molding. This reduces the use of traditional joints, decreases the weight of the transmission, decreases the part count, and improves the overall efficiency of the transmission. For a larger size MAVs, such as the Jumbo Bird, flexural joints were used to avoid long compliant segments, which may behave non-linearly and negatively affect the stability of the MAV.

3.3 Type Synthesis

The most popular topology in this survey is the four-bar linkage, which is used in seven of the MAV projects. It is a relatively straightforward design, which can transform either a rotational or translational input into a reciprocating flapping motion. The five-bar linkage mechanism is the second most popular with four of the MAV projects. Different control strategies have been implemented to utilize this extra DOF, which will be discussed in the next section. Two six-bar linkages have been used in the selected MAV projects. Both designs couple two different planar mechanisms to produce the desired flapping motion. In the Jumbo Bird MAV, the coupling of a crank-slider and a dyad allows symmetry and stability in the flapping motion. In contrast, the MFI transmission allows amplification of the linear actuator through the use of a slider-crank coupled to a four-bar linkage. The last linkage based system, the Lissajous MAV, is a double spherical scotch yoke mechanism, and exhibits a very cumbersome assembly process.

The Nano Hummingbird demonstrates a unique transmission, which offers advantages and disadvantages over the traditional linkage-based mechanisms. The Nano Hummingbird originally used serially coupled four-bar linkages, which transitioned from double-rocker to a crank-rocker. Through the testing of prototypes, the design exhibited mechanical wear, radial play in the bushings, decreased efficiency, and failure. The decision was made to institute a double-pulley drive, as it reduced the number of bearing surfaces, the amount of oscillating mass, and the overall weight of the transmission. Another possible solution may have been the implementation of compliant joints, which would also reduce the number of bearing surfaces and improve the efficiency.

Since the adjacency matrix was originally designated for linkage topologies, special considerations were taken for the double-pulley drive. The driving cable has a variable length and was treated as a prismatic joint. The second cable does not change length; therefore, the pulley pairs or disks were treated as if they had directly meshed together as gears. Lastly, the connection between the pulley disk and the variable length cable was approximated as a lower kinematic pair.

The adjacency matrices and the associated characteristic polynomial coefficients are provided in Table 2 and 3. Two groups of isomorphism were detected when searching for equivalent characteristic polynomials. The first isomorphism was identical four-bar linkages: DelFly I, DelFly II, New DelFly II, and the LIPCA MAV. The second group consisted of two identical five-bar mechanisms: MFI Wing Differential I and II. It is interesting to note that the HMF and FWMAV are compliant variations of the isomorphic four-bar linkages, as seen in the adjacency matrices.

3.4 Mobility

As discussed in Section 2.4, insect-like kinematics requires control over three DOF: stroke, pitching, and stroke plane deviation. Otherwise, a MAV will approximate insect-like flight through the use of additional control surfaces. Another method is to incorporate an extra joint at the root of the wing, which allows the wing to rotate passively along its long axis. Control of the pitching action of wing has been noted in Tables 2 and 3. The only design to actively control all three DOF is the Lissajous MAV. Nine out of the fifteen MAVs have a single DOF transmission, and have auxiliary mechanisms to assist in the kinematics. Five transmissions have two DOF, and utilize different control strategies.

The first strategy is to actively control the DOF, to generate the desired wing trajectory. The MFI is an example of this method, where two parallel six-bar linkage transmissions are coupled to a single wing via the wing differential. The parallel six-bars are separately actuated to control the two DOF present in the wing differential. The opposite strategy of passive control is implemented in the PARITy. In the design iteration from the HMF to the PARITy, an extra revolute joint is added between the actuator and the original transmission. The idea is to allow the passive balancing of aerodynamic loading on the wings, which is similar to the concept of an automobile's differential during a turning maneuver.

3.5 Actuator Type

The majority of the MAVs included in this survey require rotary input. These nine MAVs use rotary DC motors, and the remaining designs implement linear actuators. The linear actuator based transmissions are all planar, and are specifically powered by piezoelectric actuators. The advantages and disadvantages of each actuator are discussed briefly [2, 4, 5].

The DC motor is a popular choice for MAVs, as it is reliable, versatile, exhibits high efficiency, and is readily available in the market place. Gearboxes are required to reduce the motor speed to an appropriate level, which allows the desired flapping frequency to be attained. The disadvantages of DC motors include the additional weight of the gearbox, the additional weight of a controller for brushless motors, and their limited scalability.

Lift generation depends upon the wings being able to cover a large range of flapping angles. While this may be trivial for mechanisms with continuous rotary motion, linear actuators produce little strain, and thus require mechanical amplification. In this survey, all the PZT actuators are implemented with cantilever boundary conditions and amplified with some type of four-bar linkage. The main appeal of PZTs is that they exhibit high power density and high efficiency. A major disadvantage of PZTs is that they require a high activation voltage, which is currently too large and heavy to be carried on board MAVs.

4 Conclusions

We have studied 15 recent flapping wing micro air vehicle projects from research institutes worldwide. A systematic classification approach using graph theory has been applied through the use of five criteria: workspace, usage of compliant elements, type synthesis, mobility, and actuator type. This classification of mechanisms is intended to provide the designer with a tool for assessing design alternatives and documenting the advancements in flapping mechanisms for micro air vehicles.

5 Acknowledgments

This work was sponsored by the Air Force Office of Scientific Research under contract AFOSR FA9550-12-1-0070. Opinions in this paper are those of the authors and do not necessarily reflect those of the sponsors.

REFERENCES

[1] McMichael, J. M., and Francis, M. S., 1997. Micro air vehicles - toward a new dimension in flight. DARPA document, available at http://www.fas.org/irp/program/collect/docs/mav_auvsi.htm.

[2] Klaptocz, A., Nicoud, J., Floreano, D., Zufferey, J., Srinivasan, M., and Ellington, C., 2010. "Technology and fabrication of ultralight Micro-Aerial vehicles". In *Flying Insects and Robots*. Springer Berlin Heidelberg, pp. 299–316.

[3] Conn, A. T., Burgess, S. C., and Ling, C. S., 2007. "Design of a parallel crank-rocker flapping mechanism for insect-inspired micro air vehicles". *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* **221**(10), pp. 1211–1222.

[4] Conn, A., Burgess, S., Hyde, R., and Ling, C. S., 2006. "From natural flyers to the mechanical realization of a flapping wing micro air vehicle". In IEEE International Conference on Robotics and Biomimetics, 2006. ROBIO '06, IEEE, pp. 439–444.

[5] Van Keulen, A., 2010. "Flapping wing actuation using resonant compliant mechanisms: An insect-inspired design". *doctoralThesis*, Oct.

[6] Keennon, M., Klingebiel, K., Won, H., and Andriukov, A., 2012. "Development of the nano hummingbird: A tailless flapping wing micro air vehicle". In 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition.

[7] Pornsin-Sirirak, T., Tai, Y., Ho, C., and Keennon, M., 2001. "Microbat: A Palm-Sized electrically powered ornithopter". August 14-17, Pasadena, CA.

[8] Steltz, E., Avadhanula, S., and Fearing, R., 2007. "High lift force with 275 hz wing beat in MFI". p. 3987 3992.

[9] Wood, R. J., 2008. "The first takeoff of a biologically inspired At-Scale robotic insect". *IEEE Transactions on Robotics,* **24**(2), Apr., pp. 341–347.

[10] Avadhanula, S., Wood, R. J., Campolo, D., and Fearing, R. S., 2002. "Dynamically tuned design of the MFI thorax". In IEEE International Conference on Robotics and

Automation, 2002. Proceedings. ICRA '02, Vol. 1, IEEE, pp. 52– 59 vol.1.

[11] Avadhanula, S., Wood, R. J., Steltz, E., Yan, J., and Fearing, R. S., 2003. "Lift force improvements for the micromechanical flying insect". In 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2003. (IROS 2003). Proceedings, Vol. 2, IEEE, pp. 1350– 1356 vol.2.

[12] Sreetharan, P. S., and Wood, R. J., 2010. "Passive aerodynamic drag balancing in a Flapping-Wing robotic insect". *Journal of Mechanical Design,* **132**(5), May, pp. 051006–11.

[13] Sreetharan, P., and Wood, R., 2011. "Passive torque regulation in an underactuated flapping wing robotic insect". *Autonomous Robots,* **31**(2), Oct., pp. 225–234.

[14] Zbikowski, R., Galinski, C., and Pedersen, C. B., 2005. "Four-Bar linkage mechanism for insectlike flapping wings in hover: Concept and an outline of its realization". *Journal of Mechanical Design,* **127**(4), July, pp. 817–824.

[15] Galiski, C., and bikowski, R., 2005. "Insect-Like flapping wing mechanism based on a double spherical scotch yoke". *Journal of The Royal Society Interface,* **2**(3), June, pp. 223–235.

[16] Galiski, C., and bikowski, R., 2007. "Materials challenges in the design of an insect-like flapping wing mechanism based on a four-bar linkage". *Materials & Design,* **28**(3), pp. 783–796.

[17] Galinski, and Zbikowski, 2007. "Some problems of micro air vehicles development". Vol. 55.

[18] Ansari, S. A., bikowski, R., and Knowles, K., 2006. "Non-Linear unsteady aerodynamic model for Insect-Like flapping wings in the hover. part 1: Methodology and analysis". *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,* **220**(2), Feb., pp. 61–83.

[19] Ansari, S. A., bikowski, R., and Knowles, K., 2006. "Non-Linear unsteady aerodynamic model for Insect-Like flapping wings in the hover. part 2: Implementation and validation". *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,* **220**(3), Mar., pp. 169–186.

[20] Fenelon, M. A. A., 2009. "Biomimetic flapping wing aerial vehicle". In Proceedings of the 2008 IEEE International Conference on Robotics and Biomimetics, IEEE Computer Society, pp. 1053–1058.

[21] Fenelon, M. A., and Furukawa, T., 2010. "Design of an active flapping wing mechanism and a micro aerial vehicle using a rotary actuator". *Mechanism and Machine Theory,* **45**(2), Feb., pp. 137–146.

[22] Khan, Z. A., and Agrawal, S. K., 2007. "Design and optimization of a biologically inspired flapping mechanism for flapping wing micro air vehicles". In 2007 IEEE International Conference on Robotics and Automation, IEEE, pp. 373–378.

[23] Lentink, D., Jongerius, S. R., and Bradshaw, N. L., 2009. "The scalable design of flapping Micro-Air vehicles inspired by insect flight". In *Flying Insects and Robots*, D. Floreano, J. Zufferey, M. V. Srinivasan, and C. Ellington, eds. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 185–205.

[24] de Croon, G., de Clercq, K., Ruijsink, Ruijsink, R., Remes, Remes, B., and de Wagter, C., 2009. "Design, aerodynamics, and vision-based control of the DelFly". *International Journal of Micro Air Vehicles,* **1**(2), June, pp. 71–97.

[25] Sc, B. B. B., 2010. "Improving flight performance of DelFly II in hover by improving wing design and driving mechanism". *October*.

[26] Nguyen, Q. V., Park, H. C., Goo, N. S., and Byun, D., 2008. "Flapping performance and simulation of an insect-mimicking flapper actuated by a compressed unimorph piezoelectric composite actuator". In Active and Passive Smart Structures and Integrated Systems 2008, M. Ahmadian, ed., Vol. 6928, SPIE, pp. 69281N–12.

[27] Bejgerowski, W., Ananthanarayanan, A., Mueller, D., and Gupta, S. K., 2009. "Integrated product and process design for a flapping wing drive mechanism". *Journal of Mechanical Design,* **131**(6), June, pp. 061006–9.

[28] Bejgerowski, W., Gerdes, J. W., Gupta, S. K., Bruck, H. A., and Wilkerson, S., 2010. "Design and fabrication of a Multi-Material compliant flapping wing drive mechanism for miniature air vehicles". *ASME Conference Proceedings,* **2010**(44106), Jan., pp. 69–80.

[29] Julie Watson, 2011. "On the wings of technology: Hummingbird drones". *msnbc.com*, Feb.

[30] Berman, G. J., and Wang, Z. J., 2007. "Energy-Minimizing kinematics in hovering insect flight". *Journal of Fluid Mechanics,* **582**, pp. 153–168.

[31] Howell, L. L., 2001. *Compliant Mechanisms*. Wiley-Interscience, New York, NY.

[32] Tsai, L.-W., 2000. *Mechanism Design: Enumeration of Kinematic Stuctures According to Function*. CRC Press LLC, New York, NY.

[33] Murphy, M. D., 1993. "A generalized theory for the type synthesis and design of compliant mechanisms". Phd thesis, Purdue University, West Lafayette, IN.

[34] Zupan, M., 2002. "Actuator classification and Selection-The development of a database". *ADVANCED ENGINEERING MATERIALS,* **4**, pp. 933–940.

[35] Bell, D. J., Lu, T. J., Fleck, N. A., and Spearing, S. M., 2005. "MEMS actuators and sensors: observations on their performance and selection for purpose". *Journal of Micromechanics and Microengineering,* **15**(7), July, pp. S153–S164.

[36] Gerdes, J. W., Gupta, S. K., and Wilkerson, S. A., 2010. "A review of Bird-Inspired flapping wing miniature air vehicle designs". *ASME Conference Proceedings,* **2010**(44106), p. 5767.

[37] Madangopal, R., Khan, Z. A., and Agrawal, S. K., 2005. "Biologically inspired design of small flapping wing air vehicles using Four-Bar mechanisms and quasi-steady aerodynamics". *Journal of Mechanical Design,* **127**(4), July, pp. 809–816.

Appendix

Table 1. Classification of Flapping Mechanisms

Research Group	Project	Workspace Type	Topology	Rigid Body or Compliant	Actuator Type	Transmission Mobility	Wing Rotation	Year Ref.
AeroVironment	Nano Hunmmingbird	Planar	Double Pulley Drive	Rigid Body	DC Motor	1	Active	2012 [6]
Berkeley	MFI Transmission	Planar	6-bar	Compliant Joints	PZT BiMorph	1	N/A	2007 [8]
	Wing Differential I	Spatial	5-bar	Compliant Joints	N/A	2	Active	2002 [10]
	Wing Differential II	Spherical	5-bar	Compliant Joints	N/A	2	Active	2003 [11]
Warsaw/Cranfield University	Lissajous MAV	Spherical	Double Scotch Yoke	Rigid Body	DC Motor	3	Active	2005 [15]
DRDO (India)	VTOL MAV	Spatial	4-bar	Rigid Body	DC Motor	1	Active	2009 [20]
Delft University	DelFly I	Planar	4-bar	Rigid Body	DC Motor	1	Passive	2009 [23]
	DelFly II & DelFly Micro	Spatial	4-bar	Rigid Body	DC Motor	2	Passive	2009 [24]
	New DelFly II	Planar	4-bar	Rigid Body	DC Motor	1	Passive	2010 [25]
Harvard	HMF	Planar	4-bar	Compliant Joints	PZT BiMorph	1	Passive	2008 [9]
	PARITy	Planar	4-bar	Compliant Joints	PZT BiMorph	2	Passive	2010 [12, 13]
Konkuk University	LIPCA MAV	Planar	4-bar	Rigid Body	LIPCA	1	Passive	2008 [26]
University of Delaware	FWMAV	Planar	4-bar	Compliant Joints	DC Motor	1	Passive	2005 [37]
University of Maryland	Small Bird	Planar	5-bar	Short Compliant Segments	DC Motor	2	None	2010 [28]
	Jumbo Bird	Planar	6-bar	Compliant Joints	DC Motor	1	None	2009 [27]

Table 2. Type Synthesis of Flapping Mechanisms I

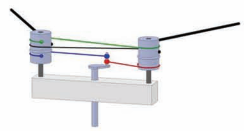
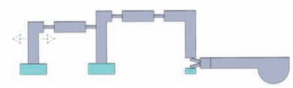
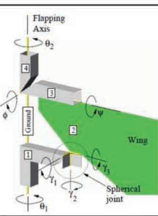
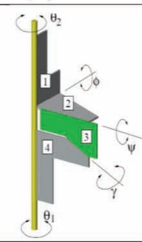
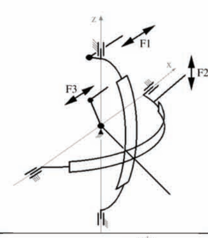
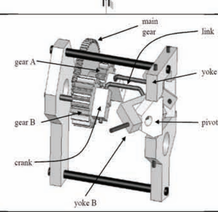
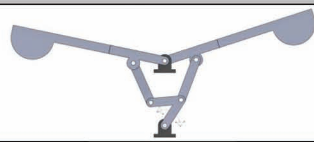
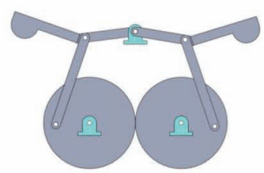
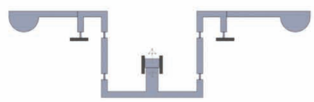
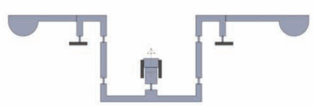
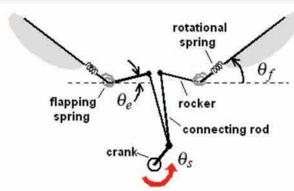
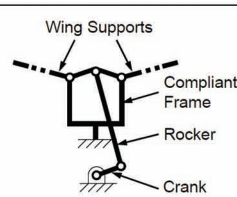
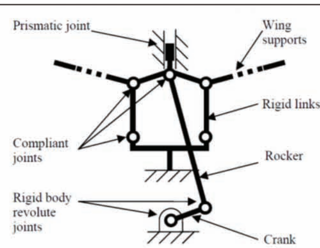
Research Group	Project	Kinematic Diagram	Adjacency Matrix	Characteristic Polynomial Coeff.
Aero-Vironment	Nano Hummingbird		$\begin{bmatrix} -1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & C & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & C & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 & 5 \\ 0 & 0 & 0 & 0 & 0 & C & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & C & 1 \\ 1 & 0 & 0 & 0 & 5 & 0 & 1 & 0 \end{bmatrix}$	$c_8=1$ $c_7=-4C$ $c_6=-34+6C^2$ $c_5=-34+129C-4C^3$ $c_4=123+135C-185C^2+C^4$ $c_3=100-324C-201C^2+119C^3$ $c_2=-128-232C+310C^2+133C^3-29C^4$ $c_1=-64+162C+165C^2-133C^3-33C^4$ $c_0=36+32C-64C^2-33C^3+25C^4$
Berkeley	MFI		$\begin{bmatrix} -1 & 2 & 0 & 2 & 0 & 2 \\ 1 & 0 & 2 & 0 & 0 & 0 \\ 0 & 2 & 0 & 2 & 0 & 0 \\ 1 & 0 & 2 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 & 0 & 2 \\ 1 & 0 & 0 & 0 & 2 & 0 \end{bmatrix}$	$c_6=1$ $c_5=1$ $c_4=-22$ $c_3=-16$ $c_2=80$ $c_1=48$ $c_0=-32$
	Wing Differential I		$\begin{bmatrix} -1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 2 & 0 \\ 0 & 0 & 2 & 0 & 2 \\ 1 & 0 & 0 & 2 & 0 \end{bmatrix}$	$c_5=-1$ $c_4=-1$ $c_3=14$ $c_2=12$ $c_1=-32$
	Wing Differential II		$\begin{bmatrix} -1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 2 & 0 \\ 0 & 0 & 2 & 0 & 2 \\ 1 & 0 & 0 & 2 & 0 \end{bmatrix}$	$c_5=-1$ $c_4=-1$ $c_3=14$ $c_2=12$ $c_1=-32$
Warsaw University of Technology & Cranfield University	Lissajous MAV		$\begin{bmatrix} -1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 6 & 0 & 0 \\ 0 & 6 & 0 & 7 & 7 \\ 1 & 0 & 7 & Y & 0 \\ 1 & 0 & 7 & 0 & Y \end{bmatrix}$	$c_5=-1$ $c_4=-1+2Y$ $c_3=137+2Y-Y^2$ $c_2=134-174Y-Y^2$ $c_1=-2-170Y+37Y^2$ $c_0=2Y+36Y^2$
Defense Research Development Organization (DRDO)	VTOL MAV		$\begin{bmatrix} -1 & 1 & 0 & 6 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 6 & 0 & 1 & Y \end{bmatrix}$	$c_4=1$ $c_3=1-Y$ $c_2=-39-Y$ $c_1=-2+2Y$ $c_0=25+Y$
Konkuk University	LIPCA MAV		$\begin{bmatrix} -1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$	$c_4=1$ $c_3=1$ $c_2=-4$ $c_1=-2$

Table 3. Type Synthesis of Flapping Mechanisms II

Research Group	Project	Kinematic Diagram	Adjacency Matrix	Characteristic Polynomial Coeff.
Delft University	DelFly I		$\begin{bmatrix} -1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$	$c_4=1$ $c_3=1$ $c_2=-4$ $c_1=-2$
	DelFly II & DelFly Micro		$\begin{bmatrix} -1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$	$c_4=1$ $c_3=1$ $c_2=-4$ $c_1=-2$
	New DelFly II		$\begin{bmatrix} -1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$	$c_4=1$ $c_3=1$ $c_2=-4$ $c_1=-2$
Harvard University	HMF		$\begin{bmatrix} -1 & 1 & 0 & 2 \\ 1 & 0 & 2 & 0 \\ 0 & 2 & 0 & 2 \\ 2 & 0 & 2 & 0 \end{bmatrix}$	$c_4=1$ $c_3=1$ $c_2=-13$ $c_1=-8$ $c_0=4$
	PARITy		$\begin{bmatrix} -1 & 1 & 0 & 0 & 2 \\ 1 & 0 & 2 & 0 & 0 \\ 0 & 2 & 0 & 2 & 0 \\ 0 & 0 & 2 & 0 & 2 \\ 2 & 0 & 0 & 2 & 0 \end{bmatrix}$	$c_5=-1$ $c_4=-1$ $c_3=17$ $c_2=12$ $c_1=-56$ $c_0=16$
University of Delaware	FWMAV		$\begin{bmatrix} -1 & 1 & 0 & 2 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 2 & 0 & 1 & 0 \end{bmatrix}$	$c_4=1$ $c_3=1$ $c_2=-7$ $c_1=-2$ $c_0=1$
University of Maryland	Small Bird		$\begin{bmatrix} -1 & 1 & 0 & 0 & 3 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 3 & 0 & 0 & 1 & 1 \end{bmatrix}$	$c_5=-1$ $c_4=0$ $c_3=14$ $c_2=0$ $c_1=-23$ $c_0=6$
	Jumbo Bird		$\begin{bmatrix} -1 & 1 & 0 & 1 & 0 & 2 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 & 2 & 0 \\ 0 & 0 & 0 & 2 & 0 & 2 \\ 2 & 0 & 0 & 0 & 2 & 0 \end{bmatrix}$	$c_6=1$ $c_5=1$ $c_4=-16$ $c_3=-10$ $c_2=32$ $c_1=12$ $c_0=-16$