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A Bibliometric Analysis of Flapping Wing Instrumentation

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Abstract: There are flapping wing-style systems being developed by various institutions around the world. However, despite there being many systems that superficially appear robust, there is no viable flapping wing flying system at this time. We identified a gap in knowledge and capability, which is that the lack of appropriate instrumentation seems to be a major roadblock in further developing flapping wing flying systems. There is no complete solution in regards to instrumentation and sensing at the appropriate scales. This paper seeks to critically examine and classify the existing instrumentation utilized and reported in the literature and attempts to identify the path forward for flapping wing-style instrumentation.

Keywords: biomimetics; instrumentation; flapping; sensing

1. Introduction

Flapping wing-style systems have been a focus of research recently, with a variety of systems being developed around the world in various configurations.

While many of these systems generate the consistent, robust movement of flapping wings, there are still no systems that are capable of replicating the performance of natural fliers with any real accuracy.

The actuation and construction of wings can be achieved through many well-understood methods, meaning the only aspect of the system that lacks development is the sensing. While true artificial flapping wing flight is still a significant distance from being fully developed, instrumentation that is fully capable of measuring system performance is a key aspect in any system seeking to achieve it [1].

Instrumentation is used in a variety of configurations in flapping wing systems, but there is still no clear instrumentation solution that is capable of measuring all key system parameters. As with any complex mechanical system, instrumentation is vital to system performance, so this lack of a complete solution is a hindrance to flapping wing development.

To attempt to better understand this deficiency in instrumentation, it is necessary to examine in depth the current state of flapping wing instrumentation to determine what aspects of the current state of the art can be combined or adapted to provide a full solution.

The overall aim of this paper is to provide a critical analysis of the state of the art in the measurement of flapping wing system performance. Specifically, it will analyze the current physical systems that measure two key parameters in flapping wing systems, loading and kinematics. Along with simulation and other supplemental testing methods, this will include looking at the methods utilized in detail and examining the advantages and disadvantages of each. It will also utilize bibliometric analysis to examine trends and data on what research work is being published around flapping wing instrumentation, along with completing the same analysis on all patents filed pertaining to flapping wing systems, with the aim of providing a full picture of the state of research on flapping wing instrumentation and highlighting the current volume of work dedicated towards it.

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This work serves to benefit the field of flapping wing research by providing a roadmap on which pre-existing forms of instrumentation can be used to measure different aspects of system performance and how these different methods can be utilized together. Understanding all of the existing methods being used is a necessary first step towards developing more full and complete instrumentation solutions for flapping wing-style systems.

This paper will cover three main phases. The first of these focuses on both the significance of flapping wing systems and their instrumentation, along with the historical context as to why the instrumentation is so important.

The second phase looks in depth at the current state of the art for flapping wing instrumentation, looking at the methods being used along with the advantages and disadvantages of all of them to try to provide deeper insight into the current gaps in capabilities,

The final phase looks at the bilbliometrics around flapping wing systems to highlight how significant the development towards these systems has been recently and the trends around flapping wing research.

This paper will only focus on wings with a flapping motion, generally those used in air. While there are other similar biomimetic systems, such as robotic fish often emulating body caudal motion, such as that shown in [2–7], or other insect-inspired systems, such as that shown by Mo et al. [8], the instrumentation in this field does not transfer to flapping wings due to the different morphologies despite any similarities. However, these systems and others do demonstrate that the complexities of biomimetics mean that instrumentation is critical, regardless of form.

As the first step in this work, it is necessary to contextualize why flapping wing instrumentation is so important in the first place.

2. Background

2.1. Flapping Wing Systems

Before highlighting the importance of the instrumentation itself, it is first necessary to understand why flapping wing systems themselves are so important.

Flapping wing systems seek to emulate the performance of fliers in nature, primarily birds and insects. This is due to the significant performance benefits that these systems have appeared to reach, as a result of evolution.

One such example is the dragonfly. They are capable of low-speed hovering and maneuverable flight, which would be emulated by a rotary-winged craft, along with high-speed flight more akin to fixed-wing systems.

Dragonflies exhibit impressive performance, such as velocities higher than 10 ms^{-1} and instantaneous accelerations as high as 25 ms^{-2} [9]. They are also capable of traveling up to 20.8 cm per wing beat [9] and achieve lift-to-drag ratios that approach 10:1 [10,11].

Their maneuverability is also shown in their ability to roll at up to 180 deg/s and yaw 180 deg within three wing beats [12].

This is only one such example, with many other insects and birds capable of high-performance flight through their incredibly well-developed and -adapted structures. If a human-built system was able to emulate these performance characteristics at any level, it would lead to a versatile craft that could fill a variety of uses, alongside the existing configurations of UAV or MAV that are currently ubiquitous.

However, there are significant challenges in building such a system. Whether looking at insects, birds or any other natural flapping wing systems, there is a lot of complexity in the means of actuation along with the kinematics of the wing itself. This means it is exceedingly difficult to emulate these motions while also generating sufficient force. These systems also require minimal mass to attempt to remain comparable to these natural systems or even achieve flight.

As such, it is necessary for any mass on a flapping wing system to be completely necessary and the system to perform as optimally as possible.

In order for any such optimization to occur, it is necessary to fully understand the forces operating throughout the system along with where any inefficiencies or losses lie to

ensure the maximum amount of energy put into the system is utilized. This understanding necessitates fully developed instrumentation that is capable of measuring all critical areas in the system for both forces and kinematics such that the system can be fully characterized and understood in order to allow further development.

At present, there is a variety of existing instrumentation that is used to measure the performance of flapping wing systems. But there is no full instrumentation solution that is sufficient enough to achieve the required characterization of flapping wing systems as will be further discussed in Section 3.

2.2. Historical Context

An alternative way to highlight the need for solid instrumentation in flapping wing systems, or any similar complex system, is to refer to the previous examples of implementations in the early stages of development.

In this particular instance, a reasonable analogy is the initial development of winged flight. There were works on flight at a human scale as early as 1799 [13], with Cayley determining that the flapping wing flight of birds was not suitable and flight would need to use fixed wings to generate lift while being powered by other means rather than using ornithopters [13,14]. He also designed wings that used a roughly trout-shaped design and a full-sized glider in 1849 [13]. In the decades that followed this, there were many attempts at flight, including various gliders, steam, compressed air and other power methods, but there were no systems that were capable of sustaining more than controlled glide [13,14].

In the late 19th century, Phillips further developed cambered airfoils similar to the modern counterparts by expanding upon Cayley's work on fixed wings, while Lilienthal created powered hang gliders with an engine moving the wing tips up and down in a fashion similar to an ornithopter [13].

These many glider flights and designs along with the development of engines by Otto meant that by the late 19th century, all the required means for flight were present: power, aerodynamic designs and experimental data. Despite this, there was still no system built that was capable of flight for any reasonable distance.

At the commencement of the 20th century, the work by Langley was also unsuccessful. But it was the work of the Wright brothers that would eventually lead to sustained flight.

The Wright brothers took a more rigorous approach to the design and build of a flying machine.

From observing that birds adjust their wing tips to create roll, they designed their wings to warp in order to control the roll of their craft [13,15,16]

This also led to them developing their gliders to turn by banking instead of by yawing as most other systems did at the time [16].

The first gliders they developed led them to build their own wind tunnel in order to test hundreds of wing geometries in order to optimize their design [13–15]. This method of computation and design is still used in modern design.

Upon adding a rudder to their third glider to control yaw and roll, their system was the first to have three-axis control [13,15].

When they were moving from gliders to powered flight, they had to construct their own motors, as no manufacturer produced a light enough engine for them [14,15]. They also had to design their own propellers, which they did through the use of their own scientific basis for propeller design and propeller theory, along with additional wind tunnel testing. This led to propellers that were 70% efficient [14,15].

The ultimate result of all of this work was that they were able to create the first system capable of extended flight. This came from methods that included the efforts of others, along with creating their own extensive designs and rigorous testing throughout the design stage.

Parallels can be drawn between the pre-Wright brothers era of fixed-wing aviation and the current stage of development of flapping wing-style systems.

There are many and diverse systems that currently exist, and many of them have achieved a level of success, with a large number of systems being capable of flight already. The knowledge of how to build and actuate these systems is already somewhat developed.

However, there is a lack of proper testing regime that could be used to ensure that these well-known methods are being used to their full capabilities to enable systems to operate at their highest performance and efficiency—both of which are necessary especially when considering the weight constraints that would impact any system trying to mimic its natural counterpart.

A full and systematic testing regime for flapping wing systems could yield better results for those being currently achieved and push the design and performance of these systems further along than they already are, in a similar fashion to the way the Wright brothers flier pushed fixed-wing aviation forward.

3. Existing Instrumentation

Many existing flapping wing systems being built around the world feature some form of instrumentation or sensing in order to test their capabilities.

Due to flapping wing-style flight still being an emergent technology, at present, the successful application of any method of instrumentation is largely shown by being able to take useful data from it, so there are few systems which are capable of flight of meaningful performance or show real-world utility outside of being an implement of research.

Any potential flapping instrumentation suite developed in the future would likely draw upon a combination or adaptation of one or more existing methods. For this reason, it is important to understand these methods and their advantages, disadvantages and potential uses in the current state of instrumentation.. In order to do this, a large number of publications on flapping wing systems were examined to determine which testing methods were present, if any. These methods were then analyzed to determine the characteristics and the uses of them.

The various methods of testing primarily fit into two main categories: loading, which focuses on the various forces that are present throughout the system, and kinematics, which focus on the motion of the various components in the system.

3.1. Loading

Flapping wing systems are complex and often have forces and losses occurring in various locations and directions, which can be complex to fully measure and define. As such, it is necessary to have instrumentation that can read these forces as accurately as possible, without affecting or causing major disruptions to the system's performance. There are various means currently used to measure the loading in flapping wing systems, and while they all have their advantages and disadvantages, there is still no complete solution. Figure 1 shows the typical locations at which the primary load sensing instrumentation is installed.

These methods shown are described in more detail below.

(Note: In the majority of publications, the instrumentation was not the main focus of the paper, and unless clearly specified otherwise, it was assumed that any load sensor was of a single axis).

3.1.1. Single-Axis Load Cell

The first and most common method for measuring load in a flapping wing system is to use a single-axis load cell. Though the concept itself is simple, there are different ways in which these sensors are used. Some have the system mounted indirectly to the sensor, through strings or beams [17–19], some mount the sensor to the mechanism through a linear air bearing [20,21], and other systems create bespoke sensors to best measure the system performance [22,23]. However, the majority of systems that utilize single-axis load cells simply mount the mechanism directly on an off-the-shelf sensor. Despite this simplicity, these directly mounted systems show robustness in measuring data at diverse flapping frequencies from less than 15 Hz [24–28], 15–30 Hz [29–32] to as high as 35 Hz [33].

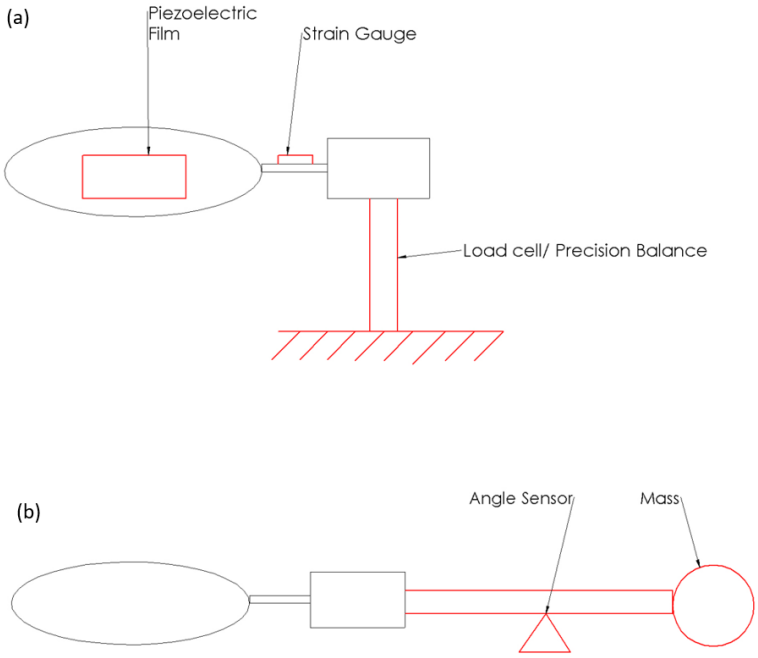


Figure 1. Typical instrumentation locations for load cells, strain gauges, precision balances, piezoelectrics (**a**) and setup for counter-weighted beam (**b**).

The major advantage with this form of instrumentation is its simplicity. Load cells are a well-understood technology that is simple to implement, and can be read relatively easily with simple electronics and micro-controllers, while outputting accurate and reliable data. These sensors can also be small and generally feature mounting points which make them easy to integrate into any system that requires them. The potential compactness of the required electronics combined with their size means that they can potentially be utilized for in-flight applications with flapping wing systems; however, their strongest use case is in bench top testing, as their simplicity in measuring data and their ability to be mounted to any system lends them to the rapid testing of the overall lift of a system.

However, these sensors are not a full and complete solution.
The first shortfall is that these sensors are only capable of reading on a single axis. This means that while they may be a simple method for measuring the vertical loading in a system, they cannot simultaneously measure horizontal loading, with the system having to be manually rotated 90 degrees relative to the sensor in order to read the other loading axis. The other major shortfall with these sensors is that the method of installation onto any system, which generally requires the system itself to be mounted atop the sensor, only measures the overall output force of the system and does not measure any of the performance within the system itself. This means that although the sensor can show changes in loading when adjustments are made to a system's configuration, it does not show where there may be inefficiencies or significant energy losses within the system.

3.1.2. Multi-Axis Load Cell

Another commonly used method for measuring flapping wing system loading is to use a multi-axis load cell. The most commonly utilized sensor is an ATI Nano 17. These sensors are mounted in a variety of ways, including indirectly mounting via a rod [34–37], mounting horizontally [38] or mounting upside down [39]. However, the bulk are mounted with the system directly atop the sensor, which is the simplest configuration. Much like single-axis sensors, the ATI Nano 17 has been shown to be capable of measuring systems operating at a variety of frequencies, such as <11 Hz [40,41], 11–19 Hz [42–47] and 20–35 Hz [48–52].

Alternative sensors utilize the same mounting methods as the ATI Nano 17, although some also opt to allow adjustable angles of attack [53,54]. Other sensors used include the ATI Mini 40 [55], ATI Gamma [56], F6D45 [57], Deltalab sensor [58], M3816BH [59], and other unspecified sensors [60].

The first advantage of this style of instrumentation is in its multi-axis operation. It means that along with the principal force generated by the flapping wing system (the vertical loading), the system is also measuring the loading in other directions. This can be on as many as six axes (three axial loads and three corresponding moments), meaning that the sensor gives a much more detailed reading of system performance than its single-axis counterparts.

This method of instrumentation also shares the single-axis load cell's advantage of usually having inbuilt mounting points and of being a well-understood method of data acquisition, with the sensors being easily available to order. This means that much like the single-axis load cell, this sensor lends itself to being utilized for the rapid testing of a system's final output.

This sensor also shares one of the shortfalls of the single-axis load cell: the system must be mounted atop the sensor itself, meaning that it does not read data on the performance of the mechanism itself, only the overall output of the system.

The other disadvantage with this method of instrumentation is that the added complexity of these sensors generally requires larger equipment in order to read them and largely precludes them from any sort of in-flight usage, impacting the portability of any form of test rig created utilizing them.

3.1.3. Strain Gauges

Strain gauges are another method used for measuring the performance of a flapping system, some examples being [61–63]. They are used by mounting them to a certain part of the system to measure the load in that area (e.g., on the spars or root of the wing, or on the spars in the mechanism). Strain gauges can be either single-axis or multi-axis.

Their main advantage is in their small size, which enables them to be mounted to any location where the loading needs to be measured. This means that the forces occurring within the system can be measured and characterized with relative simplicity.

An additional advantage is in the simplicity of reading these sensors. By using them in any Wheatstone Bridge configuration, they can be read using relatively compact electronics. This combined with the small mass and footprint of the strain gauges available means that these sensors could feasibly be used for in-flight measurement, which is likely their major use case, as to use them in a benchtop testing rig would add unnecessary complexity when a single- or multi-axis load cell could be used instead.

The main disadvantage of strain gauges is that they require a suitable mounting point to be utilized within a system. They need to be mounted flat upon the piece of the system being measured—this requires the system to be designed around the sensor with features such as square shafts or flat spots to mount strain gauges; this disadvantage is more significant for multi-axis strain gauges, which have larger footprints due to their configuration. While this disadvantage of using strain gauges is not significant, it does add supplementary requirements to this method of instrumentation.

3.1.4. Precision Balance

A precision balance can also be used to measure system performance. Examples of this are in references [64,65].

This has largely the same characteristics as using a single-axis load cell to measure the forces on the system, with the only difference being the electronics on a precision balance being contained, meaning the data generally have to be measured manually rather than through micro-controllers or other methods.

This difference is the major disadvantage of this style of system, as it means it cannot be integrated into the electronics of the flapping wing system itself, and it also precludes it

from use as in-flight instrumentation due to the size of the precision balance itself, meaning that the utility of this style of instrumentation is specifically limited to benchtop testing.

3.1.5. Counter-Weighted Systems

A counter-weighted system is another method that has been used to measure the performance of a flapping wing system as seen in the work of Zárate et al. [66] or that of Mahardika et al. [67].

Zárate utilizes a beam with the flapping wing system mounted to one end, masses mounted to the other, and an angle sensor at the pivot point measuring the angle of the beam during operation.

As the flapping wing system operates, it will lift its end of the beam, causing a change in angle from which the load can be calculated.

Mahardika has the system mounted on vertical rails with a counterweight attached through a pulley. The speed at which the system falls is measured, and from that, the loading is calculated.

The advantage of these systems is their simplicity. They are capable of easily measuring any flapping wing system by swapping out the system and the counterweight. This means that they can be used to test a variety of systems in rapid succession as long as they have compatible mounting points.

The disadvantages of these systems are numerous. Firstly, the system does not measure in more than one axis; to adapt the system to measure horizontal forces would require significant additional complexity to be added to the system.

Additionally, they measure forces indirectly, which means there is no potential for in-flight instrumentation.

Due to its configuration, Zárate could be very susceptible to vibrations or any shaking near the work area, impacting the results obtained. The configuration of this system also means that measuring the dynamic or changing loads is problematic due to the counter-weighted setup and the inertia of the beam itself.

The last disadvantage of these systems is that they are not capable of measuring any of the system performance aside from the overall force, meaning any inefficiencies or losses within the flapping mechanism itself cannot be identified. Much like the precision balance, this method has utility in benchtop testing and the simple acquisition of vertical loading data from any mechanism that can be mounted on it.

3.1.6. Motor Torque Profiles

Motor torque profiles can also be used to provide insight into system loading as is shown by Conn et al. [68]. These provide the amount of torque being output by the motor during operation, which constitutes the loading being put into the system.

This method has the advantage of not requiring any additional sensors or instrumentation and being relatively simple for obtaining clear data.

The downfall in this method is that it only provides information on the torque that is applied to the system, not any of the output force. This means that even if the motor is showing high torque, it could all be lost in the mechanism, and the data would not highlight it. Therefore, this form of instrumentation does not offer any insight into the performance of the mechanism or the wing itself, only how much load is applied to it.

This has clear utility as part of a full suite of in-flight or benchtop instrumentation paired with another method that reads the system output performance. This is because it does not require any additions to implement but gives a clear indication of the load being input into the system.

3.1.7. Piezoelectric

An additional method for measuring the loading in a flapping wing system is using piezoeletric materials as shown in [32]. This particular method utilizes a piezoelectric film on the wings to measure the load they experience during operation.

The major advantage of this method is that it measures the load at the output itself, meaning that only the useful force being output by the system is measured.

However, it suffers the same disadvantage as many of the load-measuring styles in that it cannot provide all the information of the performance of the system. This means that although it is a good method to measure the output of the system, without also knowing the input, there is still no way to determine the operating efficiency of the system or any losses that may be occurring within it.

Much like the motor torque profiles, this instrumentation would have utility as part of a larger suite of instrumentation in a testing rig.

3.1.8. Summary

Overall, this variety of instrumentation can provide insight into the loading being generated in a flapping wing system. The overall loading measured by single- and multi-axis load cells, precision balances, and the counter-weighted beam method all provide a rapid indication of changes in a system's overall performance, which is a useful method of determining the impact of specific changes. The strain gauges, motor torque profiles and piezolectrics provide insight into the operation of certain aspects of the system, which may not give an indication of the overall performance but when combined with other methods of instrumentation give additional details that could be used to fully characterize a system (although strain gauges and piezoelectrics could be used to determine output power).

However, the loading is not the only critical parameter that needs to be measured in a flapping wing system.

3.2. Kinematics

Along with measuring the force that is being output by the system, it is also necessary to measure the kinematics of the wing.

This serves two purposes, the first being that it provides additional context for the loading information as long as the data is time-synchronized. This additional data means that the important values for loading can be identified as being on the upstroke, down stroke or other phases of operation, allowing areas of potential optimization to the wing stroke to be identified. The other reason the kinematics measurement is important is that it allows the validation of whether the system is actuating as expected. This allows the actual motion of the wing to be compared to the desired motion from the input, allowing issues in the system's motion to be easily identified.

The following are methods that were used to measure the kinematics of a flapping wing system, along with an analysis of the advantages and disadvantages of each. The typical usage locations for some of these kinematic sensing methods are shown in Figure 2.

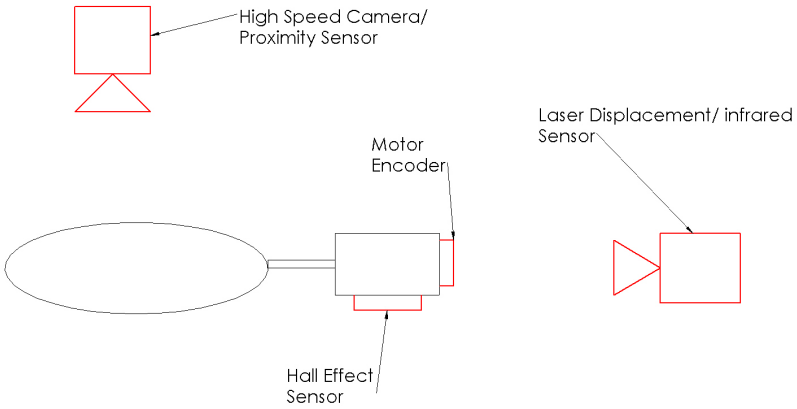


Figure 2. Typical instrumentation setup for high-speed camera, proximity sensor, motor encoders, Hall effect sensors, and optical sensors.

3.2.1. High-Speed Camera

High-speed video is a common way to measure the kinematics of the system. It can be performed in multiple ways depending on what data is required. To help track the motion of the wing, markers can be added to the wing to be better detected by the cameras. This can include strips of tape or lines [17,43]; markers on the roots, tips [34] and/or the spars [30,55]; and colored or reflective markers [48,54]. Alternatively, systems use a coating on the entire wing to allow the full motion of the wing to be observed in imagery, such as in [69,70]. A stroboscope can also be used to enhance the detection of the kinematics of the system as is used in [24], or other markers can be used as in [29,39,42].

High-speed imaging can otherwise be used without aids or external equipment to determine the kinematics of the wing. Single or multiple camera setups can be used to obtain results, whether they offer side views [33,52,56], front views [38], top views [37], a combination of front/back and side views [21,35,71,72], three-camera setups [49] or other mounting setups [25,31,68].

The advantage of utilizing high-speed video is in its simplicity. While specialized high-speed cameras can be expensive to acquire and set up, many modern mobile phones feature some form of high-speed recording, so with adequate consistent lighting and a tripod, it is relatively simple to obtain data through this method.

Also, the footage obtained using this method highlights behaviors of the wing that may not be identifiable using other methods, particularly the flexing or bending of the wing. While it is unlikely to offer an easy quantitative measure of this behavior, it still provides a level of clarity that other sensing methods cannot.

However, this leads us to the major disadvantage of using high-speed video, which is that the measurement is indirect. Even using some form of measurement aid or reference, the measurement of kinematics using high-speed footage is indirect, meaning there is a reasonable margin of error in any data obtained. It also means that the loading data cannot be directly compared to the position of the wing during operation without unrealistic levels of detail about the structures and materials.

Along with this, high-speed cameras need to operate independently of the system itself, meaning that it is not suitable for mounting for any form of in-flight measurement of system performance. One major reason for this is that the image-processing suite requires extensive computational capability, which is complex and requires large amounts of power onboard, which might easily exceed the power needed for flight.

This means that the high-speed cameras' utility is in laboratory testing, where the system is either held in place or heavily constrained so that the camera system can obtain full details on the desired motion.

3.2.2. Hall Effect Sensor

One of the alternatives for measuring the kinematics of the system is the use of a Hall effect sensor. In this instance, the sensor is used in a tachometer to determine the operational frequency of the system. Some example systems that use this method are in references [30,44–46,53,59].

Hall effect sensors lend themselves to two potential uses in flapping wing systems. The first of these is as a tachometer to output directly the flapping frequency of the system. The second is using these sensors to determine the exact position of the wing during operation, which is significantly more useful but necessitates much more complexity in the electronics and programming.

3.2.3. Motor Encoder

A motor encoder is used to measure the kinematics of the system by measuring the motion of the motor's output shaft. Examples of systems that use encoders are [37,63].

This method has the immediate advantage of being easily implemented, while providing relatively accurate information if correctly implemented.

Encoders also have the advantage of being able to provide both position and velocity information, meaning that if the flapping wing mechanism is efficient, the kinematics of the wing can be calculated from the output data.

The downside to this method of measuring kinematics is that it does not provide any direct information on the positioning of the wing itself. While this is not a major issue, it does mean that any inefficiencies in the motion of the flapping wing mechanism may not be easily identified using this method.

Much like the motor torque profiles from the loading instrumentation, the motor encoder is a useful part of a whole instrumentation suite, as it provides clear insight into the motion being put into the system.

3.2.4. Optical Sensing

Measurement of the kinematics using other methods of optical sensing comes in multiple forms.

This can include laser displacement sensors to measure the wing position [69,70] or the position of fixed points in the system such as a slider or the actuator itself [42,44,71], which can also be measured using infra-red [64]. Alternatively, particle image velocimetry can be used to measure the airflow over the wing [73] or a motion capture system to record the motion of aspects of the system during flight [74].

This method has the same advantages and disadvantages as motor encoders when measuring actuators or linear aspects of the mechanism. It can provide direct information on the motion of the system as long as the mechanism the actuators are connected to is robust; however, it does not give direct information on the position of the wing.

When directed at the wing, this method provides the positioning of the wing itself but does not give any indication of the motion efficiency of the system and mechanism itself.

Both methods require an additional module/sensor to be mounted in the system, unlike the motor encoders, which simply mount to the driving motor, though if the optical sensor is sufficiently small, this is not a significant issue.

Particle image velocimetry as seen in the work of Bin Abas et al. [73] provides a good visual indicator of airflow around the wing but does not provide detail on the wing's motion on its own.

These various optical methods are all useful as part of a laboratory-based testing setup, as, much like high-speed video, they require the system to be either fixed or heavily constrained in order to be captured by the measuring equipment.

3.2.5. Proximity Sensor

Another method that was used to determine wing kinematics was to aim a proximity sensor at the wing during operation. This sensor would then output the wing's stroke position. An example of this is shown in [26].

The advantage of this method is that it provides a direct reference as to the location of the wing during operation, unlike other methods that only provide indirect information on the wing's motion.

It can also be used synchronously with loading data, which means more context can be provided to any testing data obtained.

The disadvantage is that it requires external equipment to measure this position, meaning it may not be well suited to use for flight instrumentation, which means, much like the optical sensing methods, this instrumentation has its utility primarily in laboratory-based testing.

There is also no means to measure the angle of attack of the wing. This means that in any system that has two degrees of freedom, there is no measurement available for the second axis of wing rotation.

3.2.6. Summary

The output from these various methods of measuring the kinematics can also be used to drive the design or understand the performance of a flapping wing system. High-speed cameras can give good insight on the position and flex of a wing, which can be useful for determining the motion efficiency and kinematics of the system, though the visual operation of it means the data from it cannot be synchronized with the loading data of the system. Laser displacement sensors and proximity sensors have more potential for this synchronization, but they do not give detail on any flexing motion of the wing and may not give direct information on its position.

Hall effect sensors can potentially provide detail on the wing's position, though not easily, and they may provide a strong insight into the kinematic performance if used effectively.

Motor encoders would provide reliable insight into the operational frequency of the system but lack any means to directly measure the motion of the wing and so would be best paired with another method, even if only initially until the system behavior is understood.

The main challenge with kinematic measurements, unlike loading, is a lack of clear ways to directly measure performance at different positions in the system, as a lot of the methods either work indirectly or cannot give a full picture of the system performance.

3.3. Other Testing Methods

Along with methods that directly measure the loading and kinematics acting upon a flapping wing system described in the previous section, there are also other methods that are used to supplement these testing methods, even though they are not directly instrumenting flapping wing systems.

3.3.1. Wind Tunnel

As with any system that relies on interactions with an airstream, a wind tunnel is a useful tool in the testing of flapping wing systems to give an indication of in-flight performance.

In general, wind tunnel testing is utilized in conjunction with other instrumentation methods. Depending on the target velocity of the flapping wing system under test, the systems are tested at various maximum speeds such as 3–5 ms^{-1} [24,36,47,52,54,60], 6–8 ms^{-1} [32,40,41,58,59] or 10 ms^{-1} [28,53,61]. This variety of chosen wind velocities is due to the wide variety of flapping wing fliers that exist in nature and their respective flight velocities.

The immediate advantage of wind tunnel testing is that it provides detail on how the system will react to air movement not generated by the wing's motion (whether through system motion or the environment). This is especially useful in systems that are actuated with two or more degrees of freedom, as they are able to optimize their kinematics to draw the most useful energy from the wind while minimizing energy losses. The only disadvantage to wind tunnel testing is that the use of a wind tunnel requires space and needs nonstandard equipment to support and operate; however, it could be argued that this disadvantage is negligible when compared to the advantages offered by this testing.

3.3.2. Vacuum Environment

Along with using a wind tunnel, a vacuum environment is another means to supplement other testing methods. It entails mounting the entire system within a vacuum environment and varying the pressure. Examples of this are shown in the works of Benedict and Seshadri et al. [75,76].

The advantage provided by this is that the system's performance can be measured in a variety of different scenarios, which can represent different air pressures, altitudes or other factors. Along with this, a vacuum chamber allows some control of the aerodynamic loading of the wing during operation, which can be utilized to further characterize the wing's performance. This is particularly useful when, for example, one needs to separate aerodynamic and inertial forces.

The main disadvantage of this method of testing is that the performance of a system in a vacuum can vary significantly from its performance in a normal environment. In particular, issues can arise from lubricants not being as effective in vacuum, or lack of air for heat transfer from motors/actuators causing overheating in extended operation.

3.4. Mathematical Modeling/CFD

While it is not explicitly considered instrumentation, mathematical modeling or computational fluid dynamics (CFD) are both regularly used to gauge the performance of aspects of flapping wing systems. These techniques can be used to explore strains and forces that cannot be directly observed from outside the structures.

These methods can include the usage of mathematical modeling to determine the performance of a system, in which equations representing system performance are derived, showing the important parameters for system performance, and are also solved if it is appropriate. Such modeling is shown in [77–82].

These can also utilize CFD modeling, in which a system is defined in fluid dynamics software, and the system performance is extracted through simulation. This can be used to vary factors such as wing sizing [83], surface modifications [84–86], or moving the pivot point in folding wings [87–89]. It can also analyze changing kinematics [90,91], angles of attack [92], or other parameters [93,94]. Alongside this, it can also be used to analyze more complex interactions, especially between tandem wings, where it can analyze changing relative kinematics [95–97], aspect ratios [98], or any other interactions [99,100].

The immediate advantage of these methods of determining system performance is that they can be completed without having to manufacture any physical equipment for testing. This means that some of the complexities that are involved in constructing and testing flapping wing systems can be initially avoided while data is still obtained. Additionally, the system being analyzed can be quickly adapted as necessary, as it only requires adjusting the models instead of manufacturing new components.

The major disadvantage is that they do not measure against a physical system. This means that there are potential aspects of the system that are not fully measured, and the results obtained can only be as good as the model is complete.

Overall, mathematical modeling and/or CFD are useful components of the toolkit for obtaining and complementing performance results on flapping wing systems in the early stages of design but would likely require pairing with physical testing methods to validate the results as the design progresses.

4. Bibliometric Analysis

Along with examining the various styles of instrumentation independently, the flapping wing research was also analyzed through bibliometric analysis to better highlight the current state of the research through the relations between methods, the volume of work, where it is being completed, and what fields it is aligning with. This is important for the analysis of the instrumentation itself, as it further shows which methods are more relevant, along with the clear interest in the work of developing flapping wing instrumentation.

The initial step in this analyses is to look at which forms of instrumentation were most used. Figure 3 shows what styles of instrumentation were used in the papers examined. As can be seen, the vast majority of systems utilized only loading instrumentation or a combination of loading and kinematics. This is to be expected, as while kinematic performance is important, the amount of force being output is critical in flapping wing systems.

Due to them being the most common form of instrumentation used, load cells (single or multi axis) were analyzed to see what other styles of instrumentation were used with them in flapping wing systems. This is shown in Figure 4.

As can be seen in Figure 4, the most common pairing is load cells combined with a high-speed camera. This yields a system that is capable of giving an indication of performance in both loading and kinematics with relatively simple and well-understood methods of data acquisition.

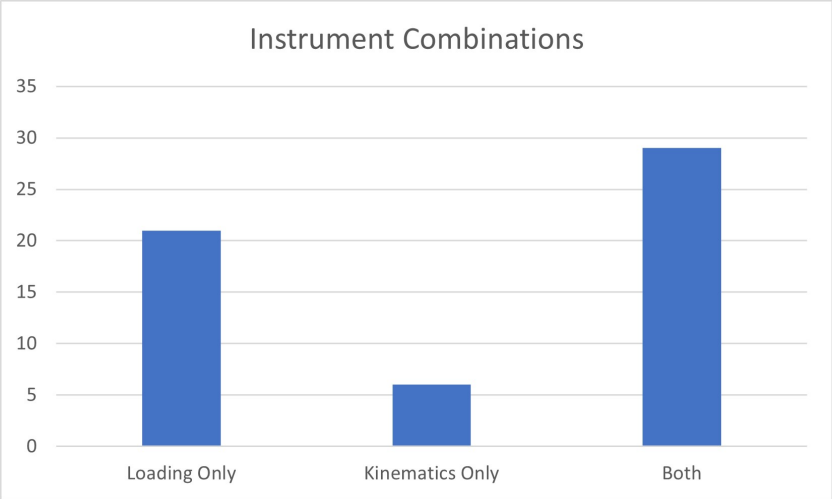


Figure 3. Forms of instrumentation used.

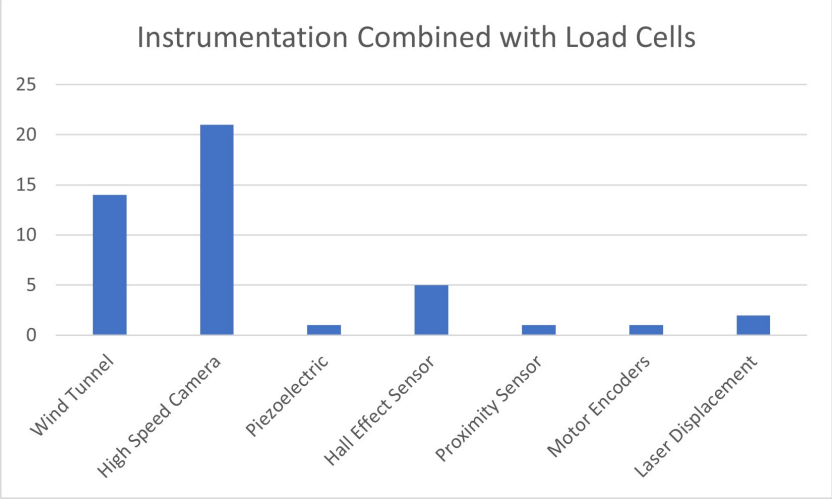


Figure 4. Methods of instrumentation combined with load cells.

Wind tunnels are the next most common method paired with load cells, which give additional information on how a flapping wing system would operate in real-world scenarios as opposed to standard laboratory testing alone.

The bulk of the remaining pairings are measuring kinematics, which is to be expected, as it serves a similar purpose to using a high-speed camera in giving additional information on performance of the kinematics in tandem with the loading. The remaining pairing was with piezoelectrics, which was likely to validate and provide additional context to the data coming out of the piezoelectric wings due to their unique design.

Along with examining these combinations of instrumentation styles, the trends in publishing around flapping wing systems were also analyzed from these papers. It should be noted that these trends only cover the papers that used or provided detail on instrumentation used with their systems. These papers were sourced using a combination of Scopus, Web of Science, and Google Scholar databases available in December 2023. Due to the focus only being on instrumentation, this database only covers a subset of all flapping wing publications.

Figure 5 shows the papers sorted by the year they were published. These papers cover a range from 2001 to 2023 (2023 having incomplete results), and as the graph shows, the number of publications is relatively steady at about two per year until 2019–2022, when the number of publications significantly increased.

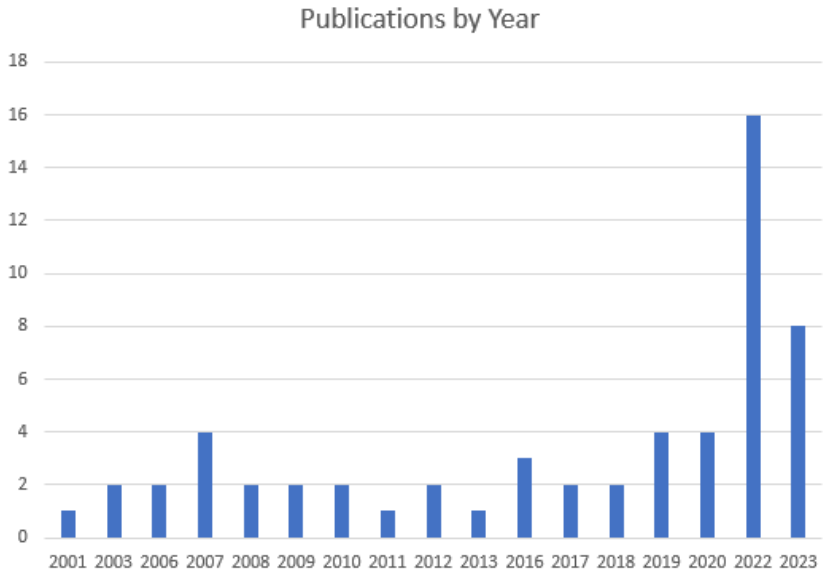


Figure 5. Flapping wing publications by year.

Figure 6 highlights the country of origin for each of these publications. This was determined by the affiliations of the primary authors from each paper. It shows that although there are papers from a variety of countries, the majority come from either China, the USA or South Korea. It should be noted that this does not take into account papers coming from the same author, so a single author publishing multiple papers can skew this dataset.

Lastly, Figure 7 shows the publications sorted by the publication areas of the journals/conferences they were published in.

As can be expected, publications regarding flapping wing systems suit a variety of subject areas and journals, combining aspects of biomimetics, mechanical engineering, control, robotics, etc. However, there are subject areas that are favored more than others, particularly robotics, biomimetics and mechanics.

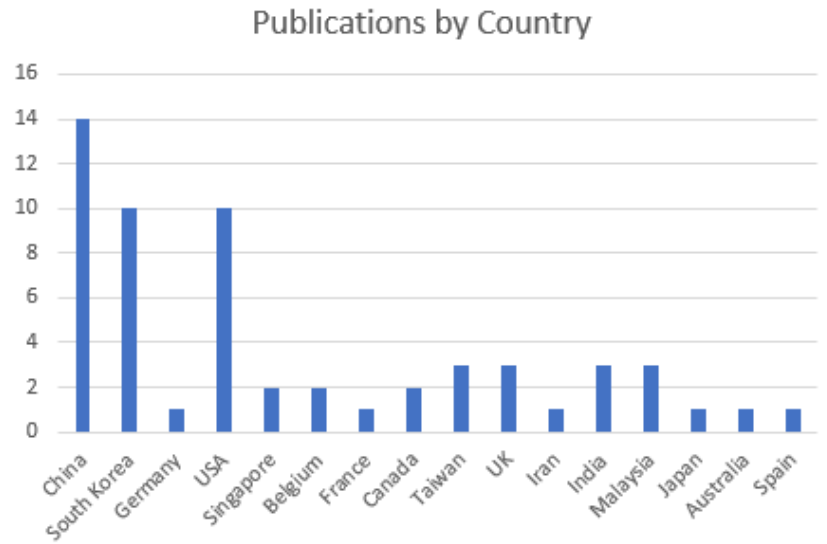


Figure 6. Flapping wing publications by country.

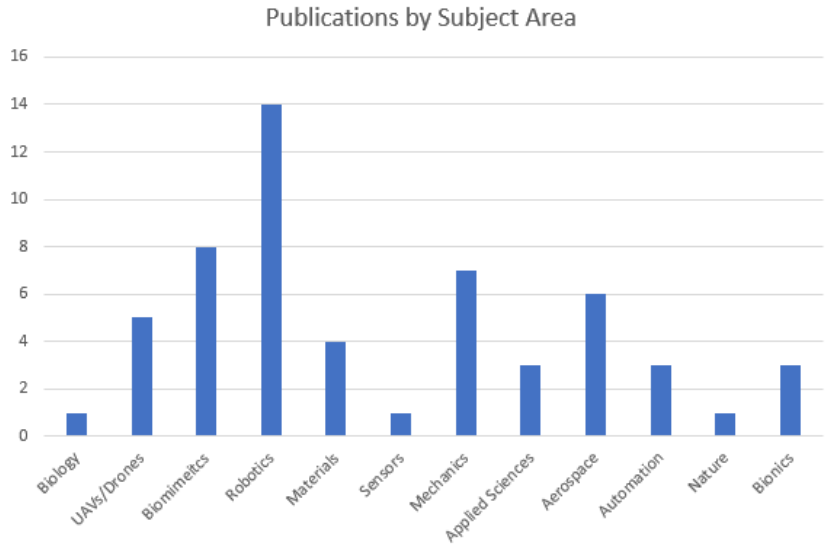


Figure 7. Subject area of publications.

5. Flapping Wing Patents

Along with reviewing the literature regarding flapping wing systems that mentioned instrumentation, patents and patent applications around flapping wing systems were also investigated and analyzed. For simplicity, patents and patent applications will be treated as the same for this section.

This analysis of patents was performed using Google Patents [101]. Although there may be limitations in using this particular search engine for patents, it collates data from patent offices worldwide, which was beneficial for this analysis.

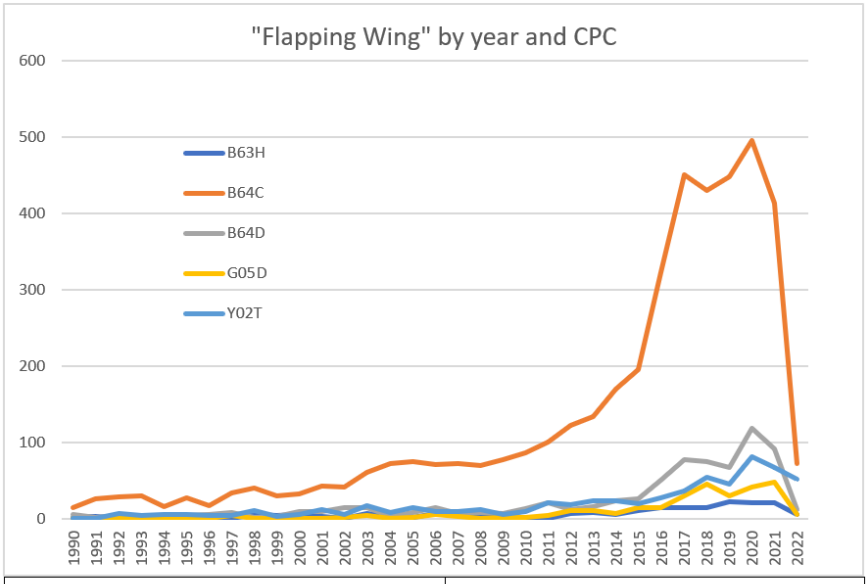
The initial search performed through Google Patents [101] for these used the search term "Flapping Wing", which yielded approximately 24,000 results. The data on these results were initially analyzed for the patent location, which is shown in Table 1. Countries/locations with fewer than 10 were not included to avoid an excessively long table. (WIPO is the World Intellectual Property Organization, EPO is the European Patent Organization). It should be noted that this dataset does not cover the entire set of 24,000 patents, instead only covering approximately 13,500 using the data obtained from Google Patents. It should also be noted that these may not all be directly related to flapping wing systems, as some may only mention the words in the patent itself; however, it was assumed that any patent which showed up in the search term was relevant, as the limitations in further processing such significant amounts of data made it exceedingly difficult to filter irrelevant patents.

Along with the patents by country, the patents were also examined by year and Cooperative Patent Scheme (CPC) codes for a variety of search terms related to flapping wing systems. These search terms in particular were chosen, as they would ensure that the data were more relevant to artificial flapping wing systems; while there are likely to be patents related to nature under only the term "flapping wing", terms such as "System", "Testing", "Performance", "UAV" and "MAV" ensured that the search was more focused on artificial systems.

As can be seen by Figures 8–13, the vast majority of the patent applications related to the search term "flapping wing ***" have occurred in recent years. These figures also show the proportion of overall patents that fall under the top five CPC codes for each search term; the majority of these fall under the CPC "B64C", with "Y02T" and "B64D" also being prominent. It should be noted that due to how the data is provided by Google Patents, there is potential overlap, so the percentages are not exact. These codes all relate to specific areas for the patents; the information on these is shown below as sourced from the Cooperative Patent Classification information [102].

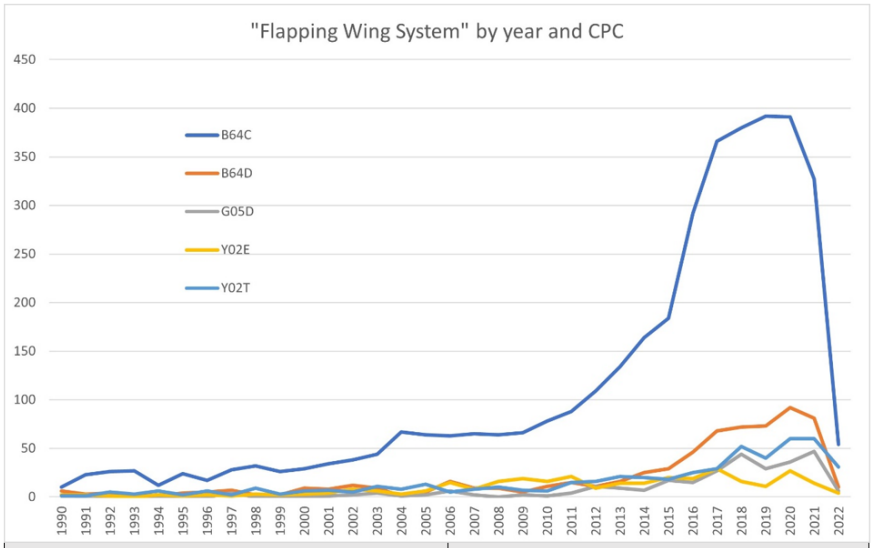
Table 1. Patent location (data source: Google Patents).

Location	No. of Patents	%
China	4546	32.58
The United States	2892	20.73
Germany	1858	13.32
Japan	1436	10.29
WIPO	456	3.27
Republic of Korea	456	3.27
EPO	421	3.02
France	346	2.48
Russia	278	1.99
The United Kingdom	273	1.96
Canada	143	1.02
Belgium	123	0.88
Austria	91	0.65
Switzerland	84	0.60
Spain	52	0.37
Australia	51	0.37
The Netherlands	36	0.26
Poland	19	0.14
Sweden	18	0.13
Mexico	16	0.11
Other	357	2.56



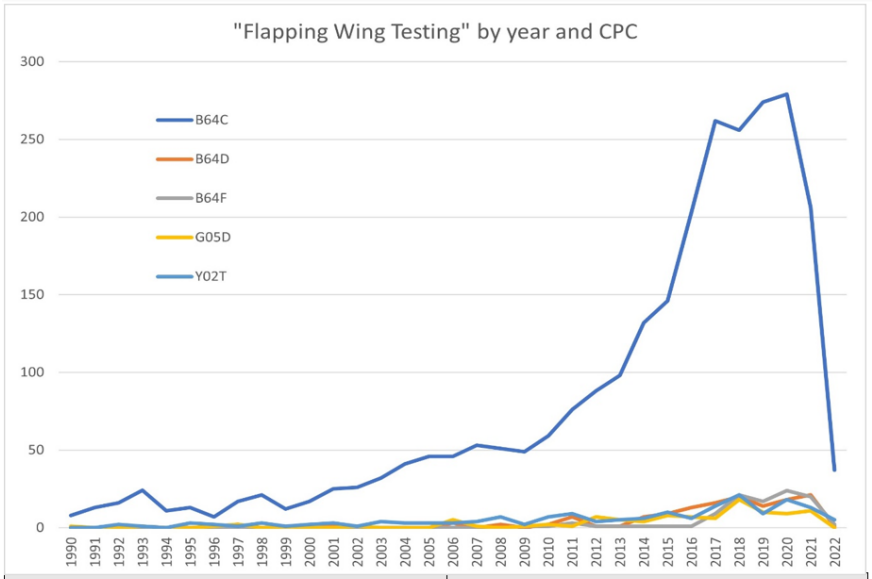
CPC	Percentage
B63H	3.45%
B64C	69.84%
B64D	11.98%
G05D	4.70%
Y02T	10.02%

Figure 8. CPC by year graph for search query "Flapping Wing". Data source: Google Patents [101].



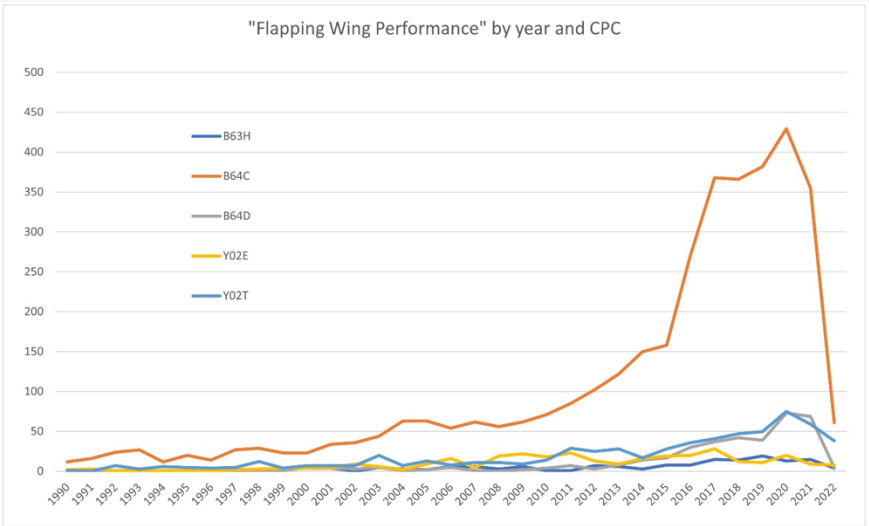
CPC	Percentage
B64C	27.07%
B64D	4.86%
G05D	2.04%
Y02E	2.32%
Y02T	3.72%

Figure 9. CPC by year graph for search query "Flapping Wing System". Data source: Google Patents [101].



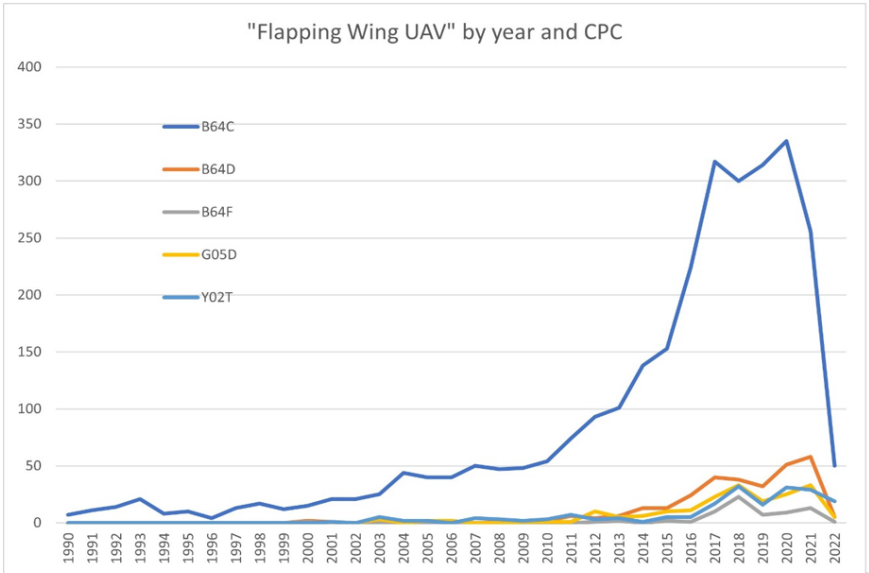
CPC	Percentage
B64C	57.07%
B64D	3.04%
B64F	2.22%
G05D	2.18%
Y02T	3.71%

Figure 10. CPC by year graph for search query "Flapping Wing Testing". Data source: Google Patents [101].



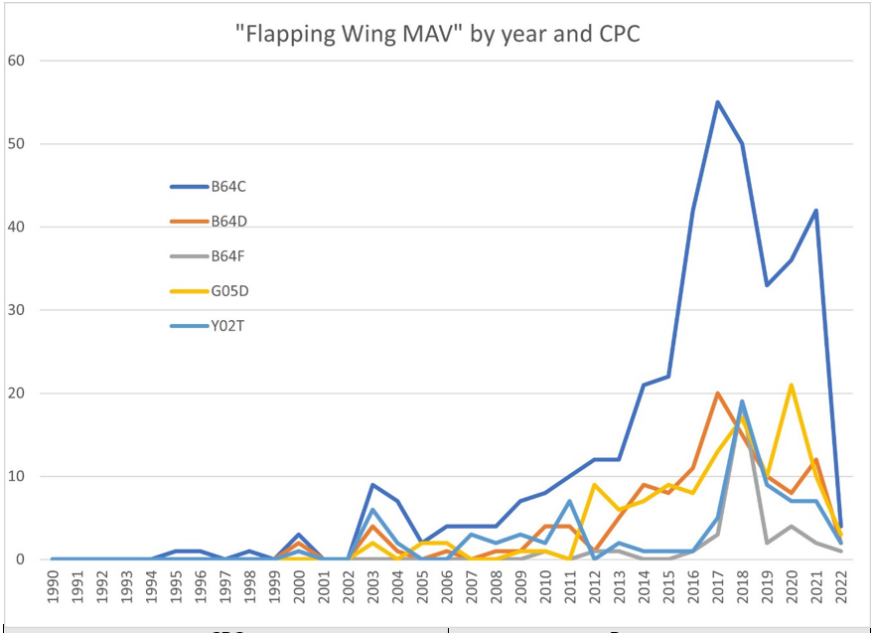
CPC	Percentage
B63H	1.54%
B64C	33.85%
B64D	3.55%
Y02E	3.00%
Y02T	5.93%

Figure 11. CPC by year graph for search query "Flapping Wing Performance". Data source: Google Patents [101].



CPC	Percentage
B64C	90.64%
B64D	9.45%
B64F	2.21%
G05D	5.99%
Y02T	6.02%

Figure 12. CPC by year graph for search query "Flapping Wing UAV". Data source: Google Patents [101].



CPC	Percentage
B64C	30.51%
B64D	9.31%
B64F	2.82%
G05D	9.47%
Y02T	6.26%

Figure 13. CPC by year graph for search query "Flapping Wing MAV". Data source: Google Patents [101].

- B***—performing operations; transporting;
- B64*—aircraft; aviation; cosmonautics;
- B64C—aeroplanes; helicopters;
- B64D—equipment for fitting in or to aircraft; flying suits; parachutes; arrangements of mounting of powerplants or propulsion transmissions in aircraft;
- B64F—ground or aircraft–carrier–deck installations specially adapted for use in connections with aircraft; designing, manufacturing, assembling, cleaning, maintaining or repairing aircraft not otherwise provided for; handling, transporting, testing or inspecting aircraft components not otherwise provided for;
- B63*—ships or other waterborne vessels; related equipment;
- B63H—marine propulsion or steering;
- Y***—general tagging of new technological developments; general tagging of cross-sectional technologies spanning over several sections of the IPC; Technical subjects covered by former USPC cross-reference art collections [XRACs] and digests;
- Y02*—technologies or applications for mitigation or adaptation against climate change;
- Y02T—climate change mitigation technologies related to transportation;
- Y02E—reduction in greenhouse gas [GHG] emissions, related to energy generation, transmission or distribution;
- G***—physics;
- G05—controlling; regulating;
- G05D—systems for controlling or regulating non-electric variables.

As this shows, the majority of patents filed are in the area of transportation regarding either aerial vehicles or watercraft. This is to be expected, as the primary use for flapping wing systems is for flight purposes, although they can and have been utilized and tested within liquid mediums.

Alongside the fields in which the patents were filed, Figures 8–13 show that in the last 10–15 years, there has been growth for all patents fitting these search parameters and that

in all but Figure 12, this growth appears to be exponential in nature. To further highlight this, all search terms were plotted by year on the same set of axes in Figure 14.

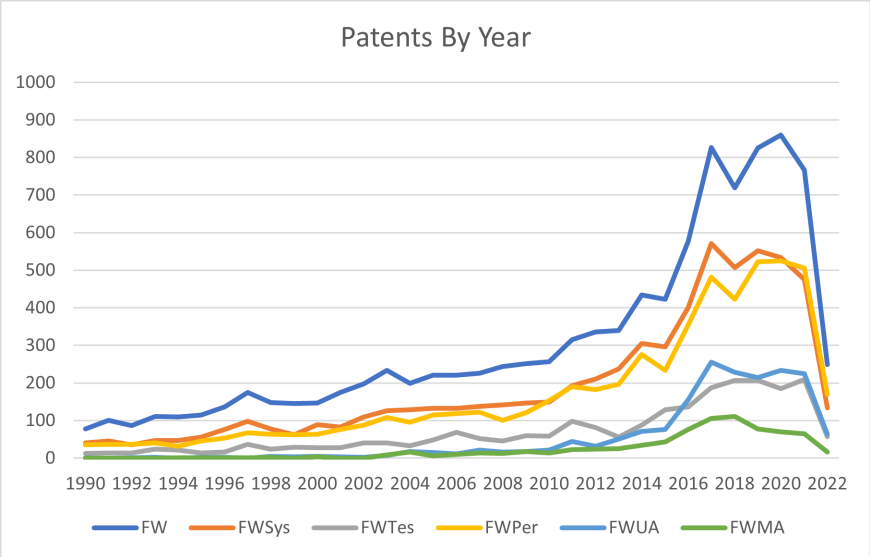


Figure 14. Number of patents filed per year from search parameters 1990–2022. Data source: Google Patents [101].

As this figure shows, all search parameters seem to follow a similar pattern, with numbers remaining relatively steady until they start to climb at an apparent exponential rate between 2010 and 2018.

This means that along with the significant research output regarding flapping wing systems in recent years, there is also a significant uptick in the patents filed, with there being an average of 800 patents filed per year regarding "flapping wing" since 2016 as per Figure 14, and approximately 17,500 pieces of academic literature written in the same time period, for an average of roughly 3000 per year according to information from Google Scholar [103].

This seemingly exponential growth is potentially due to the emergence of UAVs and MAVs in a variety of applications in recent years; from hobbyist use and photography through to military uses and surveillance. This leads to a desire for better-performing systems that are able to excel in all stages of flight and be efficient to allow longer flight duration, which are benefits that a well-designed flapping wing system would potentially be able to provide; this lends itself to the higher output from both the academic community in the literature and the business/inventor communities through patent applications.

5.1. Notable Patents

Along with examining the metrics of flapping wing patents overall, two patents with novel approaches to instrumentation were observed.

5.1.1. CN113247303A [104]

This patent describes a new method of measuring the performance of a flapping wing system, falling under CPC B64F5/60, which specifically relates to the testing or inspection of aircraft components or systems.

The proposed method involves mounting a flapping wing system to a bench-mounted lift force sensor (degrees of freedom unspecified) to measure the lift of the system. However, the entire system is enclosed within a sealed environment, which can provide variable pressure or temperature during the system's operation. This is used to simulate various altitudes of operation in a more controlled environment.

Overall, while this system is still limited by the same issues as all bench-mounted sensors, the ability to adjust the simulated environment in which the system operates offers more information on the performance of a given flapping wing system during operation in various scenarios.

5.1.2. CN115077850A [105]

This patent is for an experimental setup to record the flapping vortex of bees. It is under CPC G01M9/06 for measuring arrangements specifically adapted for aerodynamic testing.

The system utilizes a fan and a smoke generator to blow over a bee that is mounted within the system. (Note: the language of this patent makes it unclear as to whether it is a real bee or some form of artificial vehicle). The bee wing and the smoke interacting with it are recorded using high-speed cameras.

This system has similar issues to other high-speed imaging-based systems used to measure the wing kinematics. However, the addition of the smoke in the system means that a greater understanding of the interaction between the wing and the air around it during operation is possible, which could be used to optimize wings.

As can be seen from both these patents, there are clear tangents between the literature and patent applications, with both patents using methods seen within pieces of the academic literature. This both highlights the clear utility of these methods of instrumentation, and the fact that a significant number of patents emerging in the flapping wing space show that both the inventor/business community and the academic community are in the same phases in development of flapping wing systems.

There is clear drive in both of these fields to develop flapping wing systems, yet there still is no complete flapping wing solution, further highlighting the need to design a proper instrumentation suite to enable the full characterization and design of these systems.

Overall, the bibliometric analysis and the analysis of patents highlight both the current state of the research on flapping wing systems through looking at the combinations of instrumentation being utilized and showing what is working best together, and the significant amount of work being put into the development of flapping wing systems from various sources, showing the current interest in these styles of systems despite them not having a complete instrumentation setup.

6. Discussion

As the information in Section 3 shows, there are currently a variety of methods being used to measure the performance of flapping wing systems. They span from conventional methods, such as load cells, to more novel methods, such as the counter-weighted beam or piezolectric wings, through to high-speed camera arrangements.

For load-measuring methods, there is a clear deficiency in methods that provide information at both ends of the system. While systems such as the load cells, strain gauges, precision balance, counter-weighted beam or piezolectrics are able to provide information on the system's output, and motor torque profiles can provide information on the system input, there is no solution that can provide data on both.

Consequently, there is no clear means of identifying a system's efficiency or where the losses may be occurring in a system. Without this detailed data on the performance throughout a system, the only information that can be obtained from testing multiple different wings, mechanisms, components, etc., is whether there is any improvement on the previous test, not where this improvement may be occurring.

As for the kinematics measurement, there are methods that measure the performance at the wing in both high-speed cameras and proximity sensors, and there are systems to measure performance at the actuators in the Hall effect sensors, motor encoders and optical sensing.

For the systems that measure performance at the wing itself, the issue is a lack of direct measurement along with the requirement for a separate sensor to the system itself. This means that these forms of measurement are only suited to testing in a laboratory

environment and do not lend themselves to flight testing. Although data can be obtained using these methods in flight testing, they are indirect and calculated visually through the footage.

As for the other methods, most have potential utility towards use for in-flight measurement, they are largely non-invasive to the system itself, and they are compact enough that they can be used on a flight-capable flapping wing system. However, they would require the system to be first validated to ensure that the desired output comes from the measured inputs, as inefficiencies within the system can cause changes to the kinematic performance.

They would also be unable to detect any sudden changes to wing kinematics that are caused by any system failure or wear that may occur. Adaptation to such wear or damage during the life of a system will likely become a major challenge when flapping wing systems become practical.

The ideal kinematics measurements should be able to directly identify the position of the wing synchronously with any loading data provided. This would enable any loading to be contextualized with the aspect of the stroke it is in, along with providing detail on where in the wing stroke the performance can be improved.

Along with the published systems' methods of instrumentation, there are also patents which are presenting novel approaches to flapping wing instrumentation. While many patents share similarities with many existing flapping wing systems by utilizing simple and reliable instrumentation, the two patents specifically mentioned in this paper show novelty in their methods for measuring flapping wing systems, as their development shows clear tangents with novel methods in studies.

The other significant point shown in the analysis of the patents is that there is clear growth which appears exponential across all search parameters utilized around flapping wing systems. This further highlights the significant strides forward in the knowledge being developed for flapping wing systems.

However, despite this development in both the academic and applied research fields, there is still no complete instrumentation package that has emerged as the solution to characterizing flapping wing systems. We reached this conclusion after extensive critical assessment of many experimental test rigs and a few insect scale flapping wing MAVs, some that can fly for short periods and some that cannot, yet nothing operational. We may be observing a pre-Wright Brothers-like phase of development in this area of aeronautics. Limited means to optimize, adapt and refine underlying mechanisms, material selections and control systems parallel the early phase of powered fixed-wing flight.

7. Conclusions

This paper critically analyzed the current state of the art for instrumentation in flapping wing systems. This examination involved both published literature and patents (awarded and in application stage).

This yielded a deeper understanding of the various methods being utilized to measure flapping wing system performance and their frequency of use while also presenting advantages and disadvantages of these methods.

Figure 15 shows a simplified representation of where performance needs to be measured in a flapping wing system and which sensors are capable of being used in which locations. As it shows, it is important to know both the input and output on flapping wing systems so the losses throughout the power transfer mechanism can be understood.

For the instrumentation that measures loading, there is a clear trend towards using simple and reliable sensors, such as load cells and strain gauges, with a particular preference for multi-axis load cells. This is expected due to these load cells being readily accessible, easily calibrated and well understood, which eases the process of collecting reliable data from them. This provides data on the overall performance of the system and not any detail on what is occurring within it.

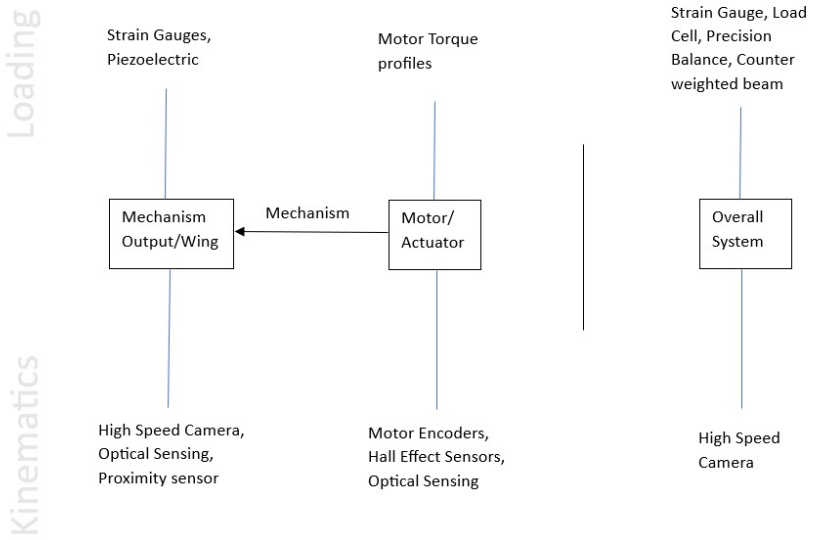


Figure 15. Diagrammatic representation of flapping wing instrumentation requirements.

There are also some more niche methods, such as using piezoelectric materials or even motor torque information to acquire performance data at different locations in the system, or supplementing sensors with a wind tunnel or vacuum environment to obtain more data in different conditions.

Overall, the deficiency in these systems in obtaining loading data across the entire flapping wing mechanism to better determine where losses are occurring is clear. Figure 15 shows there is potential for obtaining the full data from a combination of these methods, but this would start to impact the mass of the measurement system if not performed efficiently, which could preclude in-flight measurement, which is also important and complementary to benchtop/tethered testing.

For kinematics, there is a preference for high-speed footage or optical sensing. As with the loading measurements, these methods are relatively well understood, which makes the acquisition of data more straightforward. Additionally, high-speed video provides both qualitative and quantitative data, as the motion of the wing or the system can be observed, as well as being measured. This is an ideal way to measure the movement of the wing itself and, by extension, the overall movement of the system, but it does not offer insight into the motion being put into the mechanism. Additionally, these forms of measurement are not in direct contact with the system, which precludes them from any sort of flight testing.

The other methods of note, including the Hall effect sensors and motor encoders, are both more direct in their measurement of the system performance, but both read the output of the actuator/motor, meaning the motion of the wing itself is not being recorded.

Similar to the instrumentation for loading, all the necessary pieces of instrumentation to characterize the kinematic performance are present (as can be seen in Figure 15), but there is no system that has developed and implemented a full instrumentation setup to measure the kinematic performance. Unlike instrumentation for loading, however, there is not a clear way to directly measure the wing performance in flight, as the methods currently used are indirect and more suited for laboratory-based testing.

Overall, the state of instrumentation for flapping wing systems seems to be that there are a variety of existing technologies and methods being used in isolation that all provide part of the answer on system performance; however, there is yet to be a system that puts these methods together in such a way that a full, clear picture of the system performance can be obtained.

Along with the examination of the instrumentation methods themselves, this bibliometric analysis provided insight into the growth of work on flapping wing systems being completed. The data on publications mentioning flapping wing systems with instrumenta-

tion showed growth in recent years, which is likely to be reflected in similar data for all flapping wing publications, with considerable effort coming from China, South Korea and the USA in particular.

The analysis of patents also reflects this tendency, with recent trends resembling exponential growth across all search parameters used.

Overall, this paper highlights both the significant growth in work towards flapping wing systems in recent years, along with the various methods that are being used to measure and characterize these systems.

As a next step, further work needs to be performed towards creating instrumentation that can clearly identify the full performance of a flapping wing-style system. This would require an ability to measure both the input and output loading of the system, along with the real-time positioning of the wing in a way which can be integrated in a free-flying air frame.

While many of the methods shown in this paper have the potential to measure various aspects of these systems, there is still no single system that is able to fulfill all requirements. This may mean that the complete solution is one that combines the best aspects of some of the existing systems mentioned in this paper, or that the continuing growth in the flapping wing space could lead to the development of a novel method to measure performance that fulfills all requirements to characterize these exceedingly complex systems.

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