Modeling and Simulation of Kinematics for an Active Flapping and Pitching Mechanism

Afzaal M. Malik*, M. Saif Ullah Khalid**, Fahim Barlas***

Abstract— **Research in the field of Flapping Wing Micro Air Vehicle (FMAV) is an ongoing quest to mimic the natural flight in birds and insects. Birds and insects have different methods of producing lift and thrust for various modes of flight. Various species of insects have very complicated wing tip paths for hovering and forward flight while wing-tips of birds follow relatively simpler paths. The kinematics of real birds is also difficult to be mimicked because of extreme complexities involved and weight limitation for an ornithopter. Most successful ornithopters have been designed using mechanisms that generate active flapping of the wings whereas pitching is induced in the wings as a passive phenomenon due to the flexible membrane structure. Flapping frequency, flapping amplitude, incidence angle, flexibility of wings and their geometry are important design parameters for design of an ornithopter. In this work, design strategy for flapping wing micro air vehicle, and, mathematical modeling and simulation of a flapping mechanism is presented. This mechanism is capable of providing both the active flapping and active pitching to the wings. The best suited lengths of the links, the gear ratios of the power pack, the flap angle and the pitch angle for the desired design have been determined by the code FMAV1, developed by the authors in MATLAB.**

Index Terms— **Flapping wing Micro Air Vehicle, flapping and pitching mechanism, MAV, Ornithopter.**

I. Nomenclature

β wing stroke angle with respect to body
β_{max} maximum flapping angle with horizontal plane
f flapping frequency (Hz)
Φ phase Lag
Ψ pitch angle
ψ_{pin} pitch angle at pin
ψ_l pitch angle at any length
ψ_{l_t} pitch angle at any length and at any time
H_{le} amplitude of flap at leading edge
β_{inst} instantaneous value of flap angle
$\dot{\beta}$ rate of change of flap angle
ω_1 input Rpm of motor
ω_2 rpm of first reduction gaer
ω_3 rpm of second reduction gear
r_1 motor input gear radius
r_2 first reduction gear radius
r_{21} coupled first reduction gear radius
r_3 second reduction gear radius
r_4 radius of input cranks
r_{max} max distance between input crank pins
r_t instantaneous distance between input crank pins
l_1 length of coupler link
l_2 length of output link from hinge to pin
l_3 length of output link plus length of spar
l_4 length of output link
l_5 distance between two output cranks

Department of Mechanical Engineering
College of Electrical & Mechanical Engineering
National University of Science & Technology, Pakistan
Email: * drafzaalmalik@ceme.nust.edu.pk
** m.saifullahkhalid@ceme.nust.edu.pk
*** fahimbarlas@hotmail.com

II. Introduction

The design and development of micro air vehicles has got the attention of many researchers in academia and industry due to wide applicability of this vehicle in surveillance, traffic control system and many other fields of humans' interests. The FMAV platforms may provide information in the form of videos, voice and pictures from a location where direct access for relevant persons may not be possible. These vehicles may be highly maneuverable and slow-flying and are capable of flying under canopies, through alleys, or indoors to provide requisite information through communication links. Generally, ornithopters are designed with the employment of flapping motion to generate lift and thrust with passive pitching caused by the aerodynamic and inertial loads because of flexible wings.

According to Defense Advanced Research Projects Agency (DARPA) in USA, a micro air vehicle (MAV) is defined to be a small vehicle having no dimension more than 15-cm and which is capable of carrying a payload of 100-150 grams **[1]**. Many researchers have reported their MAVs' designs such as in **[2-4]**. The following flow-chart provides a systematic approach for different phases in critical design and analysis of an MAV.

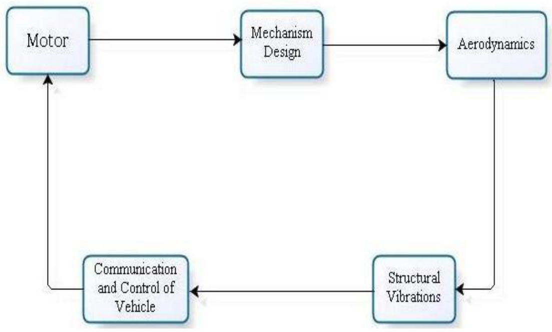

Fig. 1: Flow-chart for MAV Design Strategy

As shown in the figure 1, designers need to convert the rotary input of controlled motors into the desired flapping and pitching motion of the wings through some mechanical means. For this purpose, various mechanisms have been proposed in the literature **[4-16]**. Efficiency of eight mechanisms was compared in **[5]** in terms of efficient power transfer to wings and associated control system for the required wing motion.

It is a common engineering practice that before actual analysis of the performance of system with real-time experimentation, efforts are devoted to establish a simulated environment to examine the system computationally first so as to save time and cost. For flapping wing MAV designs, the choice of the appropriate modes for wing motion i.e. flapping/plunging, pitching and banking does play a vital role during successful mission flights. It is believed that birds and insects use wing inertia and their muscles to produce such types of motion of wing-tips that are suitable to counter wind-loadings and the atmospheric conditions to generate required lift and thrust. The authors believe that these wing motions must be controlled and adjustable during flight. Obviously, it requires enormous efforts for control but it is essential for successful MAV flights. To initiate the design cycle, two modes of wing motion; flapping and pitching, have been adopted by the authors and the designs proposed in the literature **[4-16]** have been reviewed.

A parallel crank-rocker (PCR) mechanism has been introduced in **[5]**. It performs the conversion of rotary input of motors into the flapping motion of the wing with adjustable pitching and finally angle of attack. Current work includes the mathematical modeling of this system. The modeling and simulation of these mechanisms have been presented in this paper. The basic aim for the mathematical modeling of this system is to compare certain characteristics associated with the flight modes, available in the current designs of FMAVs, using simulated environment.

The fundamental requirement for modeling mechanism, based on four-bar linkages, is to satisfy the Grashoff's conditions. It states that the sum of lengths of crank and coupler bars (the shortest and the longest links respectively) must be less than the sum of lengths of rocker and ground links **[15]**. In order to achieve maximum flapping angle, all the links must be of the appropriate lengths.

III. PCR Mechanism

The principal purpose of the flapping mechanism design is to drive the ornithopter wings in a manner that provides required lift and thrust through the utilization of unsteady aerodynamic behavior during flight, while allowing enough kinematical adjustability for flight stability and maneuvering. First, PCR mechanism **[4]** has been selected for providing flapping as well as pitching motion to the wings. It consists of a pair of PCR linkages per wing, where the output links (known as rockers) within each linkage pair are coupled according to Fig 2. One rocker link is attached to the main spar of the wing and the other to the same spar using a planer joint in such a way that it induces rotation of the spar which results in pitching motion of the wing. The wing's angle of attack can be controlled by introducing a phase lag between the two input crank linkages. This integrated method of controlling wing pitching through the frontal edges of the wing is similar to that employed by natural fliers (birds and insects). By changing the phase lag in rotation of cranks links, the angle of attack or rotation timing at stroke reversal can be adjusted. This improves control over the wing kinematics and aerodynamics.

The mathematical modeling of this system is carried out having following considerations in mind.

a. Wings are made of flexible membrane attached with spar at leading edge and wing plan-form is semi-elliptical.
b. Flapping and pitching would be induced by the power train system with equal maximum flapping angles for up-stroke and down-stroke.
c. The front spar will act as pivot for active pitching movement, caused by the rotation of the spar itself.
d. Both flapping and pitching movements are taken as periodic mathematical functions with certain amount of phase lag.
e. The completion of upstroke and down-stroke requires equal time duration.

Simple combinations of spur gears have been used to transfer the rotation to the input cranks to the wing-spar. Two-step reductions have been utilized to increase the torque and to reduce the rpm of the dc motor. The input pinion attached to the motor has a radius r_1 and angular velocity ω_1. First reduction gear has a radius r_2 and third reduction takes place at gear radius r_3.

$$\omega_1 = \text{input speed of motor}$$
$$\omega_2 = \omega_1 / (r_2/r_1)$$
$$\omega_3 = \omega_2 / (r_3/r_{21})$$

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

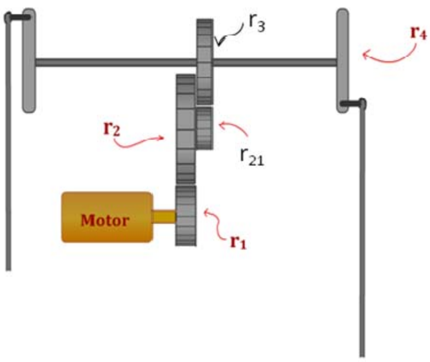

Fig. 2: Schematic Diagram of Power Pack

Fig. 3: PCR Mechanism in Wildfire Pro-Engineer

We assume that the movement of link 1 is horizontal and as the crank moves from top position to 90°, link 1 moves forward by a distance r_4 which is the radius of the input crank.

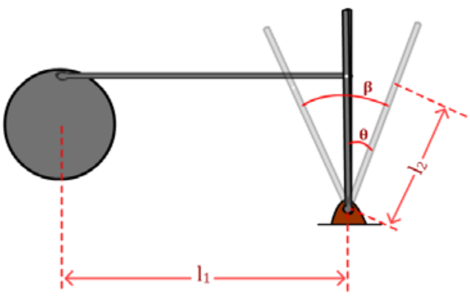

Fig 4: Schematic of Flap Angle

Thus in one stroke of the wing, the output link l_2 moves an angle of 2θ which, here, is denoted by β, the flap angle.

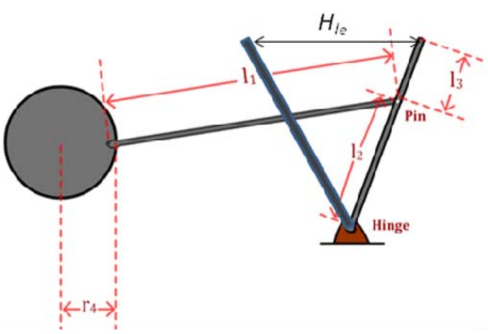

Fig 5: Dimensions of Links

From the fig 4;

$$\sin\theta = \frac{r_4}{l_2}$$

$$\theta = \sin^{-1}\frac{r_4}{l_2}$$

Also from fig 5;

$$\beta = 2\theta$$

$$H_{le} = 2l_2 \tan\theta$$

Thus H_{le} (amplitude of flap at the leading edge) can be obtained knowing the value of θ at the hinge. The instantaneous value of flap angle (β_t) can be obtained from the formula given below.

$$\beta_t = \theta_{max} \cos 2\pi f t$$

Here θ_{max} is the maximum flap angle which is β. Knowing the values of β_t at any time, rate of change of β at any time during a complete cycle can also be calculated.

$$\dot{\beta} = -2\pi f \theta_{max} \sin 2\pi f t$$

Where $\dot{\beta}$ = rate of change of flap angle.

So the flap angle at the base or at the hinge (which is the same at the spar of the wing) may be determined.

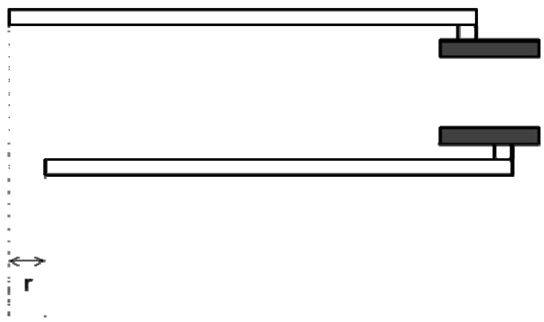

Fig 6: Vertical Distance between the Two Input Links Due to Phase Lag

The phase lag in the two input cranks acts as a source of pitching for the flapping wing. It can be seen that two input cranks are rotating with one leading the other by a lag of Φ. This lag can be pre-induced in the two cranks or can be adjustable if two input sources are used for each input crank. The instantaneous value of pitch angle can be calculated by the relation,

$$r(t) = r_{max} \cos(2\pi f t + \frac{\Phi}{2})$$

Pitch angle between the hinge and the pin is calculated and then calculations are extended for the leading edge of the wing spar by using the line-slope equations. Hence, the base, when wing is at the top i.e. completion of upstroke, the pitch angle at the pin will be φ_{pin} and it can be calculated as;

$$\varphi_{pin} = \tan^{-1}\frac{r(t)}{l_3}$$

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Knowing the pitch angle between the hinge and the pin, pitch angle at any length may be calculated by using φ_{pin} for the required length with simple slope equations for a line as follows.

$$\varphi_l = \varphi_{pin}\left(\frac{l - l_g}{l_g}\right) + \varphi_{pin}$$

$$\varphi_l = \varphi_{pin}\left(\frac{l - l_g}{l_g} + 1\right)$$

Putting the value of φ_{pin} in above equation:-

$$\varphi_l = \frac{\tan^{-1} r(t)}{l_g}\left(\frac{l - l_g}{l_g} + 1\right)$$

Thus we can get the pitch angle at any length l at any time during the rotation.

IV. SIMULATIONS & RESULTS

The comparison of pitch angle with flapping angle at varying lag angles as well as at varying link-lengths have been plotted for reference and the results, obtained from the code FMAV1, developed by the authors in MATLAB, are discussed. The best-suited dimensions for the link lengths following the Grashoff's criteria and a rotary input of 2000 rpm as rotational speed have been used as inputs.

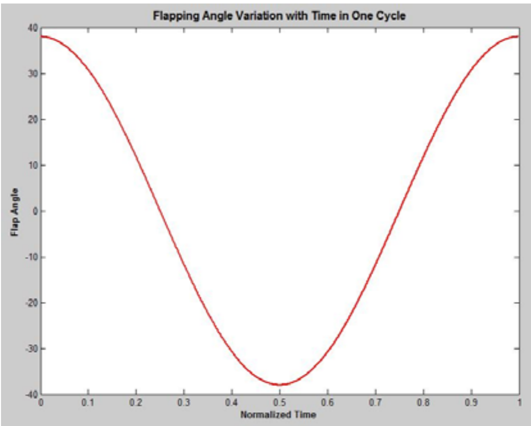

Fig 7: Flapping Angle Variation in One Cycle

Figure 7 shows that the flap angle varies from +38° to -38° having 0° at 1/4th and 3/4th positions of the cycle. The rate of change of flap angle is the highest at the centre of the stroke and its value is 0 at the top and bottom of the stroke.

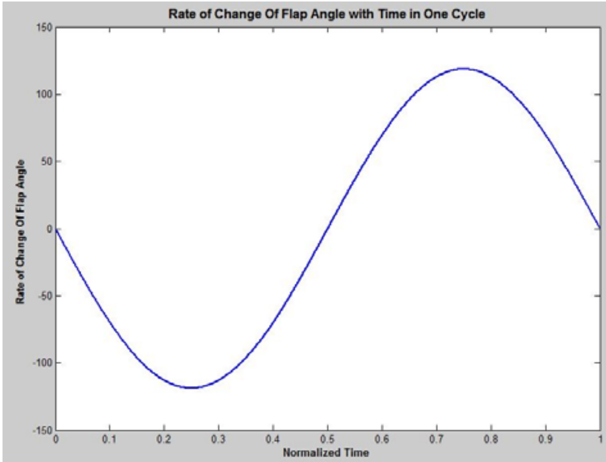

Fig 8: Rate of Change of Flap Angle

The distance between two output links is continuously changing during the cycle because of the pre-induced lag in the rotation of input links. The plot shows that the distance varies between ±28mm in one complete cycle when the lag between the two input links is set to be 90°.

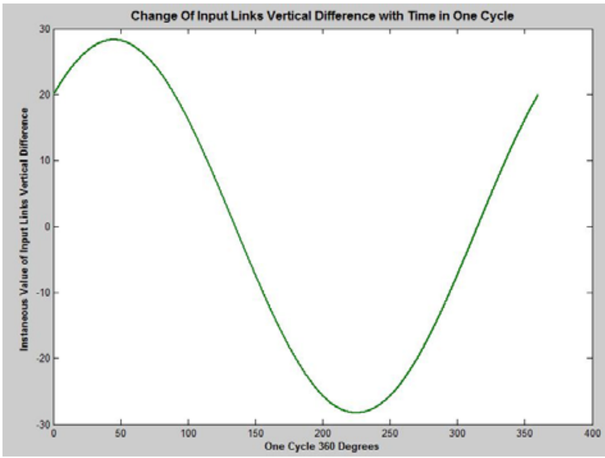

Fig 9: Input Link Vertical Difference

In figure 10, the pitch angle has been presented at a fixed length of 50 mm for varying input values of lag between two input links. The pitch angle is clearly seen to be increasing with the increase in the phase-lag input and at 0° input of phase-lag; the pitch angle shows a 0° value thus proving that there will be no pitching motion if the input phase-lag is set to 0°.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

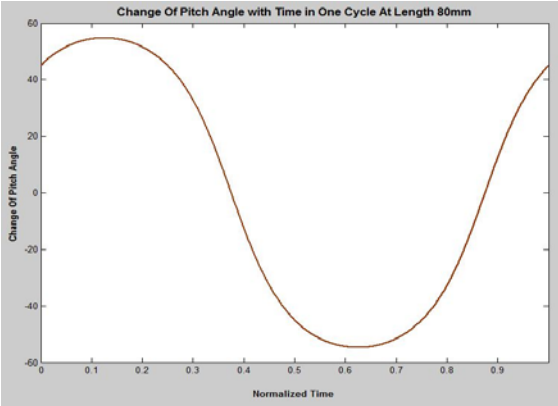

Fig 10: Pitch Angle at Length 80 mm

At length of 80 mm, the pitch angle obtained is 57 ^{o} during upstroke and a similar negative value for down-stroke is obtained.

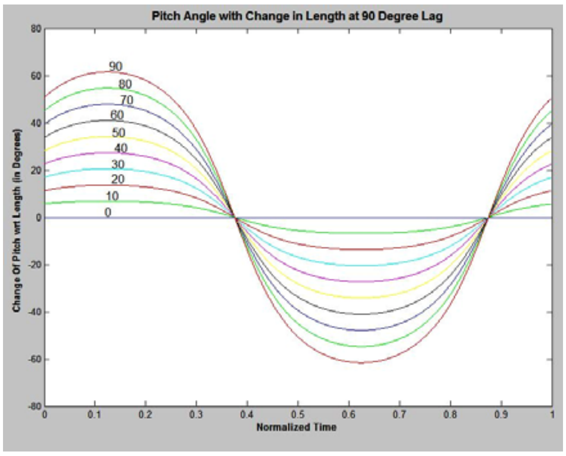

Fig 11: Pitch Angle at Lag of 90^o

Here the pitch angle variation is plotted with a fixed lag of 90^o at varying lengths and It is shown that at length 0, which is at the hinge, there is no pitching and the value of pitch increases with the increase in length to a maximum value at length of 90 mm.

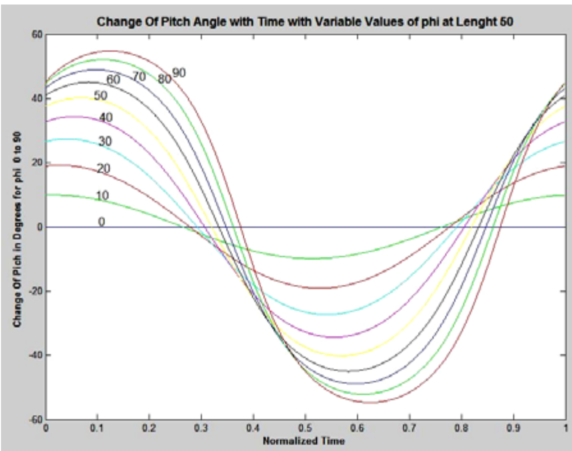

Fig 12: Pitch Variation with Change in Lag

V. CONCLUSIONS

Although there are endless possibilities of varying the inputs and getting the results in different forms but effect of only few variable design parameters has been presented here for fixed size and geometry of PCR flapping mechanism **[5]** for an ornithopter. It can be concluded from this study that:-

a. There is no pitching action at length 0 which is at the hinge and the value of pitch increases with the increase in length.
b. If the lag between the two input links is set to zero, the pitching again drops down to zero, thus for pitching to be induced, a lag of some value is required between the input links.
c. At fixed length, the value of pitch can be increased by increasing the amount of lag between the input links.
d. At fixed lag, the value of pitch is increased by increasing the length of the input links.

ACKNOWLEDGEMENTS

The authors are indebted to NUST College of Electrical and Mechanical Engineering, National University of Sciences and Technology (NUST), Pakistan for having made this research possible. We are also thankful to Higher Education Commission of Pakistan and Pakistan Science Foundation for their invaluable cooperation and support.

REFERENCES

[1] James M. McMichael and Michael S. Franci, *"Micro Air Vehicle – Towards a New Dimension in Flight"*, Available at "http://www.casde.iitb.ac.in/IMSL/MAVDOCS/www.darpa.mil/tto/MAV/mav_auvsi.html".

[2] Noriaki Tsuzuki, Shunichi Sato and Takashi Abe, *"Design Guidelines of Rotary Wings in Hover for Insect-Scale Micro Air Vehicle Applications"*, Journal of Aircraft, Vol 44, No. 1, January-February 2007.

[3] Richard J. Bachmann, Frank J. Boria, Ravi Vaidyanathan, Peter G. Ijfu and Roger D. Quinn, *"A biologically inspired micro-vehicle capable of aerial and terrestrial locomotion"*, Mechanism and Machine Theory, Elsevier, 44, 2009.

[4] Kevin D. Jones and Max F. Platzer, *"Design and development considerations for biologically inspired flapping-wing micro air vehicles"*, Exp Fuids, Spinger 2009, pp 799-810.

[5] A. T. Conn, S. C. Burgess and C. S. Ling, *"Design of a parallel crank-rocker flapping mechanism for insect-inspired micro air vehicle"*, Proceedings of IMechE Vol. 221, Part C: J. Mechanical Engineering Science, 2007.

[6] Cezary Galinski and Rafal Zbikowski, *"Insect-like flapping wing mechanism based on a double spherical Scotch yoke"*, J of Royal Society Interface, 2005.

[7] Lan Liu, Zongde Fang and Zhaoxia He, *"Optimization Design of Flapping Mechanism and Wings for Flapping-Wing MAVs"*, ICIRA 2008, Part 1, LNA1 5314, pp 245-255, Springer-Verlag Berlin Heidelberg 2008.

[8] K. D. Jones and M. F. Platzer, *"An Experimental and Numerical Investigation of Flapping-Wing Propulsion"*, 37th Aerospace Sciences Meeting & Exhibit, January, 1999.

[9] K. M. Issac, Jesica Rolwes and Anhony Colozza, *"Aerodynamics of a Flapping and Pitching Wing Using Simulations and Experimentations"*, AIAA Journal, Vol 46, No. 6, June 2008.

[10] Yotong Wang, Shankar Kalyanasundaram and John Young, *"Design and Fabrication of Dragonfly Test Bed for Aerodynamic Characterization"*, Australian Conference on Robotics and Automation 2008.

[11] D. Mueller, H. A. Bruck and S. K. Gupta, *"Measurement of Thrust and Lift Forces Associated With Drag of Compliant Flapping Wing for Micro Air Vehicles Using a New Test Stand Design"*, Experimental Mechanics, 2009.

[12] Marie Francoise SCIBILIA and Jan WOJCIECHOWSKI, *"Experimental Study of Aerodynamic Behavior in Wind Tunnels with Ornithopters and Plane Models"*, J. of Thermal Science Vol. 15, No.1, 2005.

[13] LIU Yun, Jiangang-Lv and Hongzhi-Teng, *"A New Type of Flapping-wing Mechanism and the Character Measurements"*, The 4th IEEE Conference on Industrial Electronics and Applications, China, 2009.

[14] Peng Bai, Erjie Cui, Feng Li, Weijiang Zhou and Bingyan Chen, *"A new Bionic MAV's flapping motion based on fruit fly hovering at low Reynold's number"*, Acta Mech Sin, Springer 2007, pp 485-493.

[15] K. D. Jones and M. F. Platzer, *"Flapping-Wing Propulsion For a Micro Air Vehicle"*, 38th Aerospace Sciences Meeting and Exhibit, January 2000.

[16] Darryll J. Pines and Felipe Bohorquez, *"Challenges Facing Future Micro Air Vehicle Development"*, Journal of Aircraft, Vol. 43, No. 2, March-April 2006.

[17] Robert L. Norton, *"Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines"*, 3rd Edition, McGraw-Hill, 2004.

ISBN: 978-988-18210-7-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)