PASSIVE FLUID TRANSPORT IN MICROGRAVITY ENVIRONMENTS FOR THE STABILIZATION OF ROTATING SPACECRAFT

Martin M. B. Rosales*, Eduardo J. Bidot-Lopez†, Matthew M. Wittal‡

Rotating spacecraft offers the potential to create artificial gravity for extended space missions. However, designing a guidance and control system for such vehicles involves complex considerations. This paper examines a vehicle segmented into three parts, with the propulsion unit positioned at the vehicle's center of mass. The vehicle must maintain stability around this central point, even under atypical conditions. Consequently, a durable and passive spin stabilization system is essential, requiring the passive transport of fluids. A combined system consisting of microcapillary bundles and hydraulic ram pumps is explored to transport fluids without any external energy added to the system. The dynamics of such a system are investigated, establishing performance and control limitations, and developing a control strategy predicated on the fluid dynamics between the segments. A model of the system is developed to validate the approach, showing that passive stabilization is possible, however, not as effective as an active stabilization system. Additionally, the model can be expanded for broader applications, including mass redistribution, a theoretical fluid ring, and three axis rotating systems.

Keywords: Dynamics, tether, spin stabilization, capillaries, fluids

INTRODUCTION

Rotating spacecraft can provide artificial gravity for long-term space missions [1], but the design of a Guidance and Control scheme for these vehicles is nuanced [2]. Spin stabilization is a a proposed schema for stabilization space craft in microgravity environments [3] utilizing the conservation of angular momentum to stabilize the spacecraft. Rigid body stabilization is a simplification of a fluid-filled system, as fluid slosh provides considerable complications in the controls [2], as the fluid sloshes and shifts the center of gravity to off-nominal locations. For a three-segment vehicle with the propulsion element located at the center of mass, the vehicle must stabilize itself about this point even in the event of various off-nominal circumstances. Thus, a robust and passive spin stabilization system is needed. Through the passive transfer of fluids, this can be achieved, by shifting the center of gravity to control the angular velocity and therefore self-stabilizing [2]. Utilizing a passive system for the stabilization of the spacecraft allows for reduced fuel usage, a critical resource that should be reserved for mission-critical usage.

Furthermore, for long-term deep space missions, artificial gravity is pertinent for the safety and the health of the occupants, as well as mission-critical experiments and instruments on board. The design of a guidance and control scheme for these vehicles is nuanced, therefore the development of an infallible system is critical. For a rotating spacecraft with a propulsion element at the center of mass, the vehicle must stabilize itself

*OSTEM Intern, NASA Kennedy Space Center, FL 32899, Embry-Riddle Aeronautical University, 1 Aerospace Blvd., Daytona Beach, FL 32114

†OSTEM Intern, Granular Mechanics and Regolith Operations Laboratory, NASA Kennedy Space Center, FL, 32899 USA, University of Central Florida, 4000 Central Florida Blvd, Orlando, FL 32816

‡Automation and Robotics Systems Engineer, Granular Mechanics and Regolith Operations Laboratory, NASA Kennedy Space Center, FL 32899, and Ph.D. Candidate, Embry-Riddle Aeronautical University, 1 Aerospace Blvd., Daytona Beach, FL 32114

around this point, particularly in the event of off-nominal circumstances [2İThis rotation inherently produces a centripetal acceleration. Increasing the angular velocity to sufficient speeds of the spacecraft will increase this acceleration and produce artificial gravity at the extrema of the system. About the center of mass of the system, the centripetal force produced by the angular velocity of the system will be zero. This non-constant acceleration further increases the complexity of the system for fluid transport. Therefore, a system designed to passively stabilize a rotating spacecraft producing an artificial gravity requires extensive design of the fluid transport system and the relevant control schemes [4, 5].

PASSIVE FLUID FLOW

Two primary methods of passively fluid flow are explored and a combined system is proposed to passively transport fluids in a microgravity environment to develop and design a passive method of stabilization in rotating spacecraft for use in long-term deep space missions.

The first method of fluid transport explored is a hydraulic ram pump. Also known as ram pumps and hydraulic rams, these pumps have historically been used in agricultural applications to passively transport water uphill, across large distances [6]. Although these pumps have been superseded by more efficient methods, with higher volumetric flow rates in modern agricultural applications, they still serve the important purpose of being able to transport water without external energy added to the system in environments where external energy is scarce or unavailable, this has been utilized to transport fluids as required. This is a promising type of pump for passive fluid flow because ram pumps operate entirely from potential energy and can pump fluids against the force of gravity. Ram pumps require a source of fluid located above the pump to allow the fluid to build momentum as it enters the pump increasing the pressure in the first chamber, forcing a valve closed to force the water through the exhaust pipe in a cyclical manner.

The max volumetric flow rate of a hydraulic ram pump is determined through equation 1:

$$Q_h = \eta * \nu * \frac{h_i}{h_o} \tag{1}$$

Q_h refers to the delivery flow of the hydraulic ram pump. The efficiency of a hydraulic ram pump, η varies between 50 and 70% for the most efficient ram pumps available. ν refers to the feed flow, which is determined from the flow rate going into the ram pump. $\frac{h_i}{h_o}$ is the relation between the feed head and the delivery head, respectively. pressure difference between the inlet and outlet valves of the hydraulic ram as determined by the gravitational potential energy.

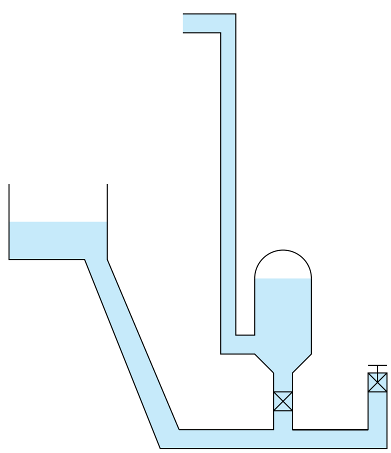

Figure 1: Cross-sectional diagram of a simplified ram pump, depicting the required elevation differences and the location of the various valves.

The second method of the passive transport of fluids is microcapillaries. Microcapillaries utilize capillary action to transport water, particularly in medical applications. Furthermore, trees use systems of capillaries to transport water and nutrients in some cases- hundreds of feet against gravity. Capillary action, also known as capillarity, is an inherent property of fluids when the adhesion to the walls of its container is greater than the intramolecular forces between the molecules of the liquid [7]. This is entirely passive and can allow large quantities of fluid to flow without external energy added to the system.

However, the ability of capillarity is dependent on the fluid itself and its ability to "wet" the capillary that it travels through. Wetting or the ability to "wet" refers to a fluid's ability to maintain contact with a solid surface [8]. A common example of a wettable fluid is liquid water, while an unwettable fluid would be liquid mercury. In microgravity environments where hydrostatic pressure is absent, capillary forces can allow fluids to travel meters [9].

The flow rate from capillary action is determined through Poiseuille's equation, as follows:

$$Q_c = \frac{\pi * r^4 * \Delta P}{8 * \mu * L} \tag{2}$$

The variable r refers to the radius of the capillary, ΔP refers to the the pressure difference, in this case being the gravitational pressure of L, the distance from one end of the capilliary to the center of the spacecraft (20 meters). Finally, μ refers to the the viscosity coefficient of the fluid being used.

A bundle of tubes was determined to be optimal based from a microporous analysis [10], however, to simplify the mathematical model the capillary is modeled and referred to as a single entity with constant volumetric flow rate across the entire surface of the capillary.

Futhermore, the pressure required for capillarity to occur is as follows:

$$P_c = (P_w - P_{nw})gh \tag{3}$$

P_c being an important value to determine if the pressures with in the system are large enough to induce a capillary affect and therefore allow for the microcapillaries to function as intended.

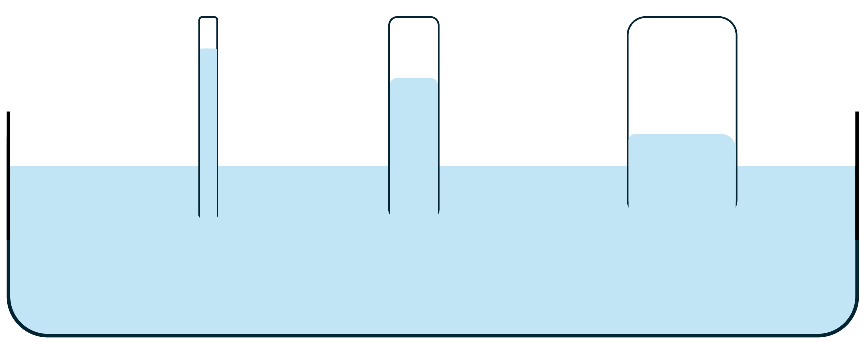

Figure 2: Diagram showing that a smaller diameter increases the capillarity of the fluid, allowing it to travel further distances against external forces.

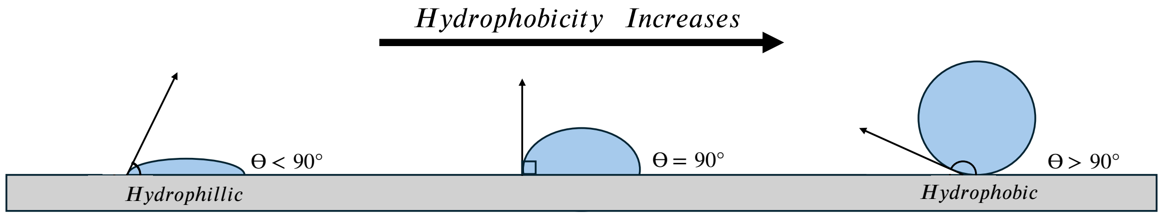

Figure 3: Diagram showing the wetting angle and how it relates to the hydrophobicity of a fluid on a solid surface.

COMBINED SYSTEM

A theoretical system was modeled that uses both a hydraulic ram and a system of capillaries to transport water from one end of the rotating spacecraft to the other end. This proposed system will primarily be passive, and in the event of off-nominal dynamic circumstances, the system should be able to self-correct without additional fuel being used and additional energy being inputted into the system.

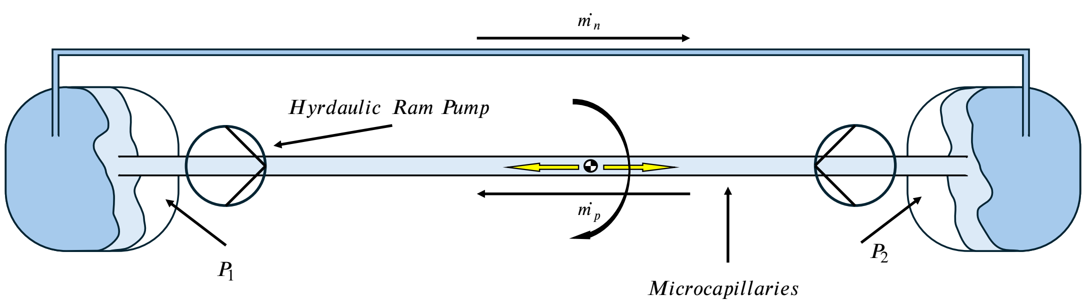

Figure 4: The internal diagram of the fluid flow between the elements in the rotating frame. Incompressible, potable water flows from the right to the left, increasing the mass of the left element and forcing the non-potable water back to the right as pressure increases.

Utilizing just one of the methods of passive fluid transfer proved difficult with constant flux due to the change of acceleration from the center of mass to the extrema, with the capillary method becoming less effective towards the extrema of the system and the ram pump becoming more efficient towards the center of mass. Therefore, this combined model will maximize the fluid flow to maintain a passive stabilization system that will work in off-nominal circumstances.

Furthermore, with a rotating system gravity is dependent on the rotational velocity of the spacecraft, therefore the rate of change of the gravity is different from the earth. Assuming constant angular velocity the max acceleration is at the extrema of the system, however, the acceleration moving towards the center of the system approaches zero (or microgravity), linearly. This is shown in Figure 5.

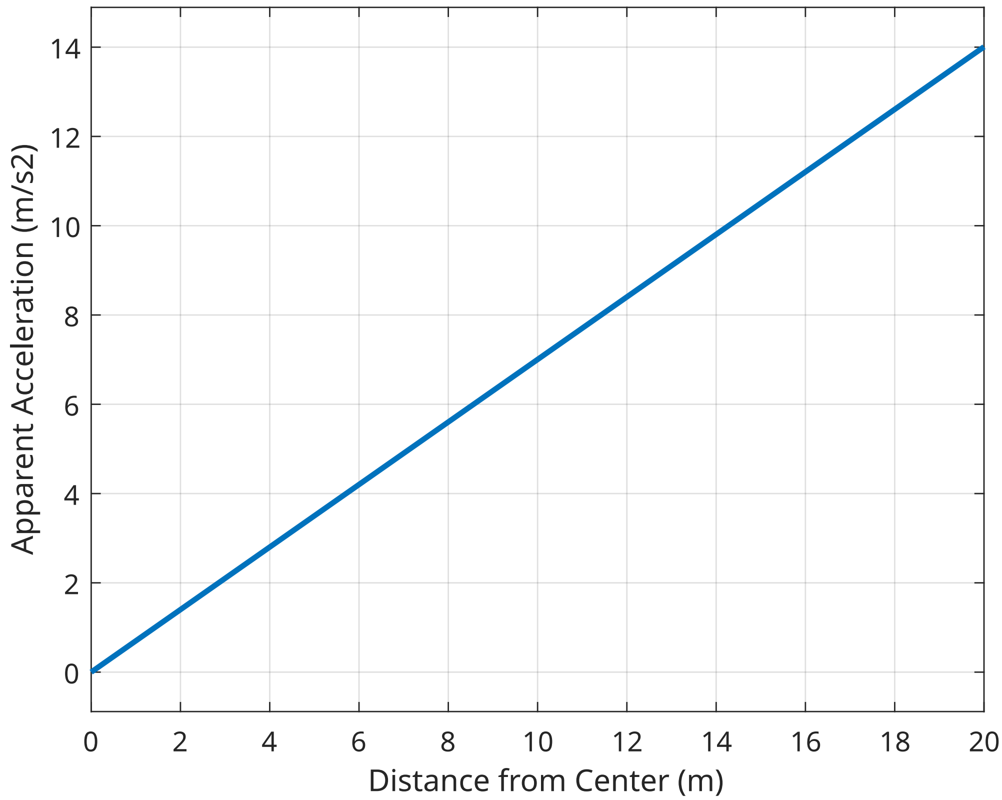

Figure 5: Graph depicting the relation of the apparent acceleration and distance from the center of mass of the system.

FLUID DYNAMICS AND MATHEMATICAL MODEL

The simulation developed determines the feasibility of the combined system. This simulation is built upon Navier-Stokes equations for fluid dynamics. The fluid in question is water, being modeled as an incompressible, inviscid Newtonian fluid to create a relatively accurate model of the system that would be constructed. Due to the nonlaminar fluid flow, the Colebrook-White and Darcy-Weisbach equations will be used to determine the major pressure and head loss of the system. These equations essentially consider the system to have a conservation of global and liquid masses as well as the mixture momentum. The Navier-Stokes continuity equation, VOF equation, Colebrook-White equation, and Darcy-Weisbach equation are as follows, respectively:

$$\frac{\partial \rho}{\partial t} + \rho \boldsymbol{\nabla} v = 0 \tag{4}$$

$$\frac{\partial \rho \alpha}{\partial t} + \rho \boldsymbol{\nabla} \alpha v = 0 \tag{5}$$

$$\frac{1}{\sqrt{\lambda}} = -2log\left[\frac{2.51}{Re\sqrt{\lambda}} + \frac{\frac{k}{d_h}}{3.72}\right] \tag{6}$$

$$\Delta p_{major\_loss} = \lambda \left(\frac{l}{d_h}\right)\left(\frac{\rho_f v^2}{2}\right) \quad (7)$$

Where $\hat{x}$ is the unit vector of the gravity direction, ρ is the density of the fluid, λ is the Darcy-Weisbach friction, l is the length of the pipe, v is the velocity of the fluid, d_h is the hydraulic diameter. The inviscid-flow assumption is guided by the expected Reynolds number (Re) values to observe in the system based on preliminary modeling. Re is dependent on the fluid properties (i.e., ν), bulk flow velocity through the tether along with the tether's hydraulic diameter and is given as

$$Re = \frac{V_{avg} D_h}{\nu}, \quad (8)$$

where V_{avg} is the average (or bulk) flow velocity, D is the hydraulic diameter of the tether, and ν is the kinematic viscosity of the fluid. The Reynolds number was determined to be in the order of magnitude of 10^8, implying that the fluid will be hyper-turbulent, meaning that the fluid can be assumed to be inviscid, which all surface forces exerted on the boundaries of each small element of the fluid act normal to these boundaries. Modeling inviscid fluids is ideal because the fluid acts with minimal external forces.

The configuration of the fluid vessels is illustrated in Figure 4. The non-potable fluid in the return is incompressible, isothermal, and inviscid, and thus the only considerations are the change in acceleration on the fluid container from the dynamical system and the change in pressure of the air in the tank. It is assumed that the mass of potable water flowing from right to left is driven by a "pump" and held constant and thus not affected by the change in pressure on either side. It is also assumed that both pipes are filled and have no air bubbles. At the start of the simulation, the right side contains 750kg of potable water and 450kg of non-potable water, while the left side contains 50kg of potable water and 250kg of non-potable water.

An augmented form of Bernoulli's principle is applied as

$$P_h + \frac{1}{2}\rho v^2 + \rho \ddot{r}_h r_h - \delta P dt = P_c + \frac{1}{2}\rho v^2 + \ddot{r}_c(R - r_h) \quad (9)$$

$$v = \sin(P_h - P_c)\sqrt{||2\left(\frac{P_h - P_c}{\rho} + \ddot{r}_h r - \rho \ddot{r}_c (R - r_h)\right)||} \quad (10)$$

Using this, the return mass flow rate - that is, the mass flow rate of the non-potable water - may be modeled as a function of velocity, density, and cross-sectional area as

$$\dot{m}_n = v \rho A_r \quad (11)$$

The term δP in Eq. 9 is the augmentation to Bernoulli's equation that allows the consideration of energy loss due to viscous effects. For this, the Darcy-Weisbach equation is applied as

$$\delta P = \frac{f_D \rho v^2}{2 D_H} L \quad (12)$$

where L is the length of the tube, $f_D = \frac{64}{R_e}$ is the Darcy friction factor, and D_H is the hydraulic diameter. For small-diameter pipes such as what is considered in this work, the hydraulic diameter is taken to be equal to the pipe diameter D.

These equations form the basis for a mathematical model, critical for determining the effectiveness of the system. First, the pressures must be determined, including the pressure created from the artificial gravity produced by the angular velocity of the system, the pressures required for capillarity to occur, and the pressures required for the return pipe to actively transport the fluid back to the other tank.

Once the pressures are established the volumetric flow rate is determined through the capillaries and if sufficiently high enough, allow the ram pumps to pump the fluid against the force of the artificial gravity.

Furthermore, the shifting of the center of gravity can be determined based on the volumes of fluid in each reservoir at any given point in time.

Furthermore, the center of gravity has to be identify to to determine where which pumps and valves have to be opened to allow fluid transfer and allow for the system to stabilize. To achieve this a simple numerical method was established that determines the center of gravity of a system using a system of weighted sums, as shown below in a simplified python script. This allows for expansion into three dimensions and an infinite number of reservoirs in the system.

```
def calculate_center_of_mass(points, masses):

    # Calculate the total mass
    total_mass = np.sum(masses)

    # Calculate the weighted sum of coordinates
    weighted_x_sum = np.sum(points[:, 0] * masses)
    weighted_y_sum = np.sum(points[:, 1] * masses)

    # Calculate the weighted average for the x and y coordinates
    center_of_mass_x = weighted_x_sum / total_mass
    center_of_mass_y = weighted_y_sum / total_mass

    # Output the center of mass
    return np.array([center_of_mass_x, center_of_mass_y])
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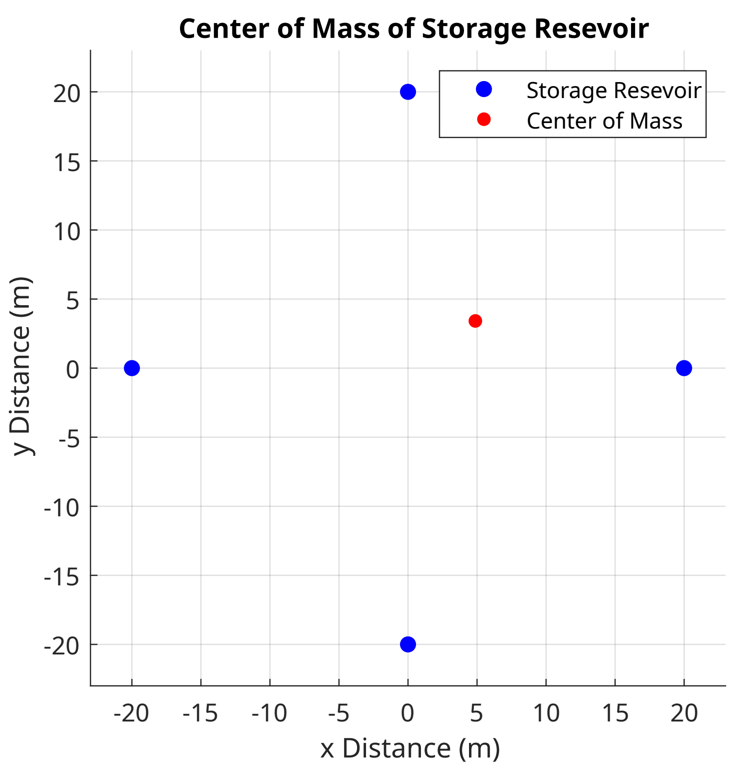

Figure 6: An example of the output of the center of gravity function within the model for a four-reservoir system. This function can be expanded to an infinite amount of reservoirs and three axes if required.

RESULTS

Combining the steps from the sections above and various equations the gravitational pressure was determined to be 3.9127 MPa.

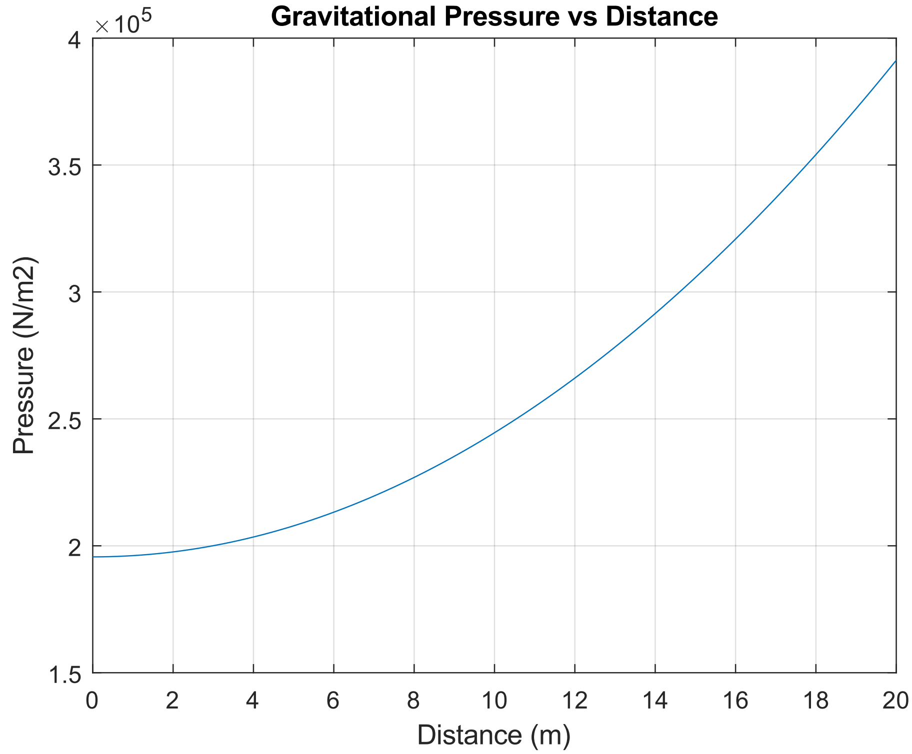

Figure 7: Graph depicting the gravitational pressure experienced from the center of the spacecraft (0,0) to the extrema of the spacecraft.

Capillary pressure can be determined from equation 3, assuming values of 9.81 m/s^2 and a length of 20 meters, producing a result of 7.691 x 10^{-2} MPa, considerably less than the gravitational pressure of 3.9127 x 10^{-1} MPa, therefore, capillary action will occur. Depending on various manufacture parameters, ram pumps require different flow rates through the inlet to function, however, on average a flow rate of .0189 m^3/s will be sufficient enough to operate current ram pumps on the market. Equation 2 was utilized to determine the flow rate though the capillary system, achieving a volumetric flow rate of .0882 m^3/s, this theoretical flow rate through the capillaries is considerably higher than the lower limit required for the ram pump to function, therefore, the ram pump can work and with an increase of flow rate at the ram pump inlet increases the flow rate at the ram pump outlet to be .0309 m^3/s.

CONCLUSIONS AND FUTURE WORK

The preliminary fluid dynamics model should determine the volumetric flow rate of the fluid through the system and therefore if the system is feasible for a passive stabilization system. Furthermore, this model will be expanded upon for further testing by removing various assumptions to create a more accurate model. Research into the effect of microgravity on wettability is also required as microgravity environments may affect how fluids wet, greatly impacting how the fluid will flow through the microcapillaries. Further iterations can include incorporating potential hydrophobic interior surfaces of the microcapillaries to increase the volumetric flow rate of the fluid used for passive stabilization.

The method of passive fluid transfer between two reservoirs is feasible in microgravity, however, an auxiliary pump can be added to the system to increase the volumetric flow rate for faster and more active stabilization of the rotating system. Inherently rotating systems maintain their momentum so a large force has to be produced from the movement of the fluid to change any rotational characteristics of the system.

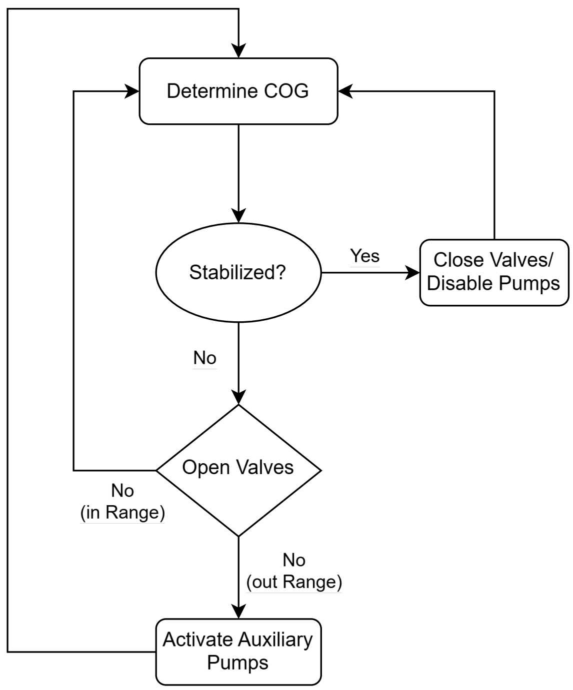

Figure 8: Psuedo code flow chart of how the system functions and calls back to the center of gravity function to ensure a stabilized system.

Figure 8 shows how a full control scheme would integrate a passive and active control system together. "Range" refers to various variables to determine if the system is not stabilized outside of the control range of the passive system, this includes a massively off-center center of gravity, excessively high or low angular velocity, and many other variables. A fully developed system requires fail safes to allow for the override of the passive system. Though the control valves allows for limited active control of the system, a back up centrifugal or axial flow pipe would allow for more drastic changes to the system in off-nominal circumstances.

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