# Feasibility Study of a Robotic Science Arm on Future Martian Rotorcraft

**Cole Rutter**
Aeromechanics Intern
NASA Ames Research Center
Moffett Field, CA, USA

**Mackenzie Lach**
Aeromechanics Intern
NASA Ames Research Center
Moffett Field, CA, USA

## ABSTRACT

Science arms are indispensable tools for planetary exploration, allowing vehicles to interact with and manipulate their surroundings in a manner similar to a human field geologist. A majority of the rovers and landers sent to Mars, beginning with Viking I and II in 1976, have made extensive use of these articulated, arm-like devices that allow for sample collection, surface preparation, instrument positioning, and the deployment of ground-contact sensors. Although proven useful, traditional rovers and landers are limited by the rough and difficult terrain of Mars. However, given the successful demonstration of flight on Mars by the Ingenuity helicopter, efforts are underway to outfit larger rotorcraft with science payloads to allow them to explore Mars' surface and lower atmosphere with significantly more efficiency than land vehicles. Such vehicles could also be designed to work in tandem with landers or rovers. The Mars Science Helicopter (MSH) is a conceptual hexacopter design that is currently under early development by both NASA Ames and JPL. Equipping a vehicle like MSH with a science arm has the potential to further expand its scientific capabilities. This paper approaches the mission and design requirements to equip a science arm on MSH while highlighting the unique technical challenges for robotic arm and science instrument capability. Current plans for MSH development do not include the addition of a robotic arm to the vehicle. However, it is anticipated that future variants of the MSH design might well incorporate such adaptable surface interactive capabilities.

## NOTATION

| | |
|---|---|
| $a$ | speed of sound (m/s) |
| A | area of rotor, $\pi R^2$ ($m^2$) |
| D | section drag (N) |
| L | section lift (N) |
| g | gravity ($m/s^2$) |
| M | Mach Number, $[M = V/a]$ |
| $N_b$ | Number of blades |
| R | rotor radius (m) |
| Re | Reynolds number |
| T | thrust (N) |
| V | velocity (m/s) |
| $V_{tip}$ | tip speed (m/s) |
| α | angle-of-attack (deg) |
| ρ | atmospheric density ($kg/m^3$) |
| σ | solidity, $\frac{N_b cR}{\pi R^2}$ |
| μ | dynamic viscosity (kg/m s) |

## INTRODUCTION

### *Early Mars Rotorcraft work and Ingenuity*

Early work into Mars rotorcraft at NASA Ames Research Center began in the late 1990's (Ref. 1). This work focused not only on the conceptual design of such vehicles but also on their fundamental aerodynamic performance (aero-performance) characteristics. Additionally, a small subset of this early Ames work considered the operational demands of such vehicles, including testing of RC-controlled and autonomous surrogate aerial vehicles for Mars rotorcraft as Mars-analog sites on Earth. Some of this operational testing of surrogate vehicles at analog-sites included vehicles with heavily-modified Commercial-Off-The-Shelf (COTS) robotic arms as well as other surface interactive devices incorporated/integrated into the platform (Refs. 2-4). When the Ingenuity Mars Helicopter development effort was started in the 2014-2015 time frame, NASA Ames was a partner with JPL from nearly the very beginning of the effort.

In April 2021, Ingenuity became the first vehicle to be successful at controlled flight on a planet other than Earth. It arrived at Mars attached to the underside of the Perseverance Rover two months before its historic first flight. Ingenuity was intended to complete a minimum of one flight, with the potential for up to five flights. It has far surpassed this number, successfully executing 16 flights (Ref. 5). As its intended purpose was to demonstrate that sustained flight on Mars is possible, Ingenuity carries no payload apart from navigational cameras, performance-monitoring sensors, a battery and solar panel, and an avionics computer. It is lightweight at 1.8 kg. Ingenuity's mission was extended into an operations phase

[1]Presented at the VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, CA, Jan 25-27, 2022. This is a work of the U.S. Government and is not subject to copyright protection in the U.S.

to support Perseverance's mission by scouting ahead for the rover, identifying potential routes and science targets.

Ingenuity's success has shown both that sustained flight on Mars is viable despite its challenging environment, and that rotorcraft vehicles have the potential to be highly useful and versatile tools in planetary surface exploration. Ingenuity, as well as the Dragonfly rotorcraft mission to Titan planned to launch in 2026, have the potential to pave the way for future missions at Mars and across the Solar System.

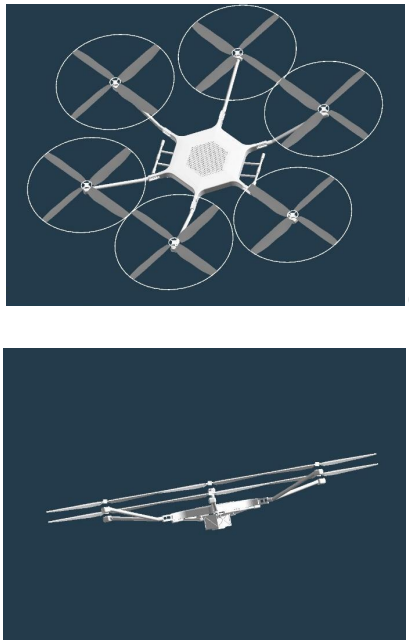



**Figure 1:** Representative Baseline (no robotic arm) of Mars Science Helicopter: (a) isometric view and (b) side view of inflight and retracted landing gear.

### *Possible Next-Generation Mars Rotorcraft: Mars Science Helicopter (MSH)*

A major next-step for Martian rotorcraft is to develop a vehicle that is capable of conducting a science mission by itself or in tandem with a rover or lander. One mission concept currently under development jointly at NASA Ames Research Center and JPL is the Mars Science Helicopter (MSH) (Fig. 1). MSH is currently envisioned as an approximately 31 kg, solar powered hexacopter capable of carrying a small payload (5 kg) of scientific instrumentation. It will make a solo traverse of Mars' terrain and lower atmosphere to carry out in-situ measurements of the surface, subsurface, or atmosphere. Depending on the mission-specific science objectives, these measurements may encompass mineralogical, chemical, geomorphological, or geophysical investigations. A whitepaper submitted to the recent 2023-2032 Planetary Science and Astrobiology Decadal Survey (Ref. 6) discusses several plausible mission concepts for MSH.

### *Beyond MSH: a possible MSH-RA (MSH with Robotic Arm) Variant*

Prior work on MSH (e.g. Ref. 7) has only briefly considered the possibility of incorporating a robotic arm onto the aerial platform in order to conduct more ambitious surface interactive science (Fig. 2). The focus of this paper is to examine the scientific justification for including a robotic arm (and deployable scientific instruments) on a Mars rotorcraft and then, from an engineering perspective, to consider the design requirements and technical challenges of incorporating such a robotic capability into a rotary-wing aerial platform.

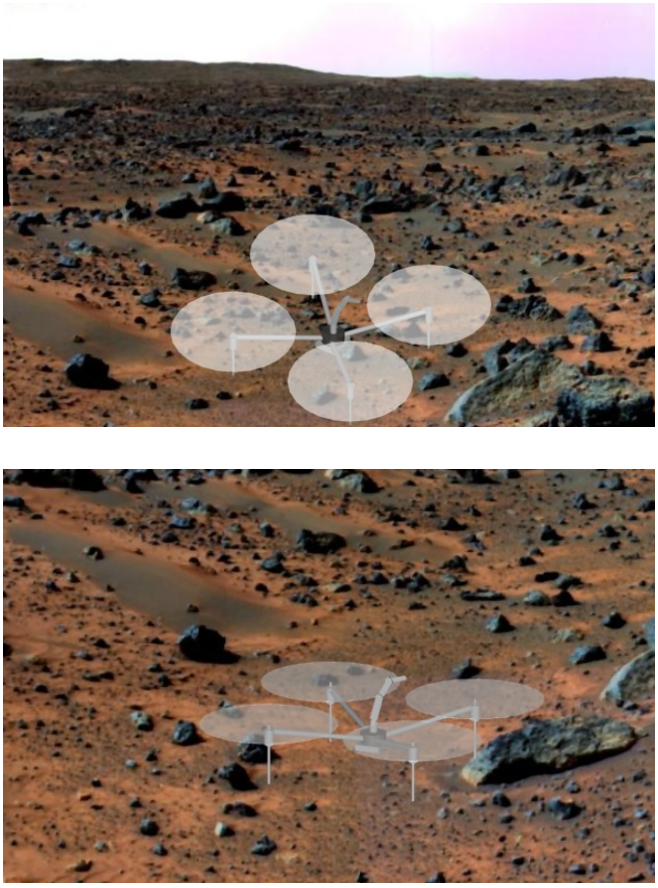


**Figure 2:** Fundamental Representation of Mars Rotorcraft and a Robotic Arm. Background image credit: NASA-JPL/Caltech.

## Scientific Rationale for a Rotorcraft-based Robotic Science Arm

Due to the strict mass, power, and volume constraints on any vehicle sent to a planetary surface,

especially a rotorcraft to Mars, it is imperative that these resources are allocated efficiently in a way that best enables accomplishment of the scientific objectives. With a 5 kg payload constraint, instruments' weight and volume must be taken into careful consideration alongside their potential scientific impact.

An illustrative example is the instrument suite carried aboard Perseverance. One component of the rover's payload is the SuperCam instrument suite, consisting of a unit mounted on the rover's mast and a unit of electronics contained within its body. SuperCam is highly versatile and is capable of remotely examining the chemical composition, mineralogy, and texture of rocks within a roughly 2-7m radius of the rover at Jezero Crater (Ref. 8), which may long ago have been host to potentially habitable environments. It is capable of a variety of spectroscopic and imaging techniques, including laser-induced breakdown spectroscopy (LIBS), spectroscopy in the visible and near-infrared, time-resolved Raman and luminescence spectroscopy (TRR/L), and optical imaging. However, despite its apparent usefulness and versatility to a wide array of studies, the combined mass of both the rover body and mast components is approximately 10.8 kg (Ref. 8), more than twice the maximum payload mass of MSH. Smaller, fewer, and lighter-weight instruments must be considered instead to meet requirements. These same considerations must be applied to a science arm. A science arm could take up mass and volume that could instead be allocated to another instrument, so its science benefit must be significant enough to justify doing so.

***Motivation: Mars Exploration Program Analysis Group (MEPAG) Goals***

A useful benchmark for estimating the scientific value of a particular investigation is the MEPAG document. The Mars Exploration Program Analysis Group (MEPAG) is a committee of Mars science experts whose goal is to help steer NASA's Mars Exploration Program (MEP). MEPAG reviews current science questions regarding Mars and selects those that represent the highest-priority science, condensing them into a hierarchy of wide-reaching goals, with more specific objectives, sub-objectives, and investigations. The MEPAG committee publishes these goals in a public report, which is updated approximately every two years, or when there have been significant enough advancements in Mars science to justify updating Mars science priorities. The most recent document was released in 2020 (Ref. 9). This document serves to guide the planning of future missions for NASA's MEP, and it also contributes to the Planetary Science and Astrobiology Decadal Survey. The current iteration of the MEPAG report organizes identified science objectives underneath four major goals.

The first goal relates to the question of life on Mars, with two objectives: to directly search for life in environments that may be likely to support it, and to study abiotic organic chemistry on Mars. Despite its currently cold and dry climate, Mars could have been a good candidate for life in its early history when it was possibly warmer and wetter. There is the chance that these conditions could exist on Mars today, possibly deep beneath the surface. Evidence of past life could be found closer to the surface, an area which could be easier for a small science platform such as a rotorcraft to access. There are plans for landers or rovers to drill deeper (e.g. Ref. 10), but studies like this could pose significant challenges to a rotorcraft with limited available mass and power resources.

Goal 2 deals with the Martian climate and is split into three objectives dedicated to understanding Mars' current climate, its recent climate, and its ancient climate. An important proxy for studying Mars' climate at any point in time is water: measuring the abundance, distribution, and seasonal and temporal flux of water vapor in Mars' current atmosphere is important not only for understanding its current climate, but also for understanding its habitability for present or past life on Mars and for future human and robotic explorers. Mars is believed to have undergone orbital variations throughout its history that have likely led to significantly different climates over long periods of time. In particular, any changes to Mars' orbital obliquity would have altered the amounts of solar radiation reaching its surface, majorly impacting climate, atmospheric properties, and weather patterns (e.g. Ref. 11). The MEPAG document identifies Mars' lower atmosphere as an important place to study climate, which is currently inaccessible to both rovers (more than several meters above the surface) and to satellites. Prospective rotorcraft vehicles have the potential to take direct measurements of Mars' planetary boundary layer or deploy small weather stations for wide-coverage surface data.

Many geologic formations on the surface of Mars display much resemblance to those on Earth. Others appear to have no analogues on Earth. The early history of Mars is believed to have been similar to the Earth's, with the latter being difficult to study due to crustal recycling processes that have destroyed this early crust. However, these processes do not exist on Mars, leaving evidence of its very early history intact within its crust. The third MEPAG goal is thus to "understand the origin and evolution of Mars as a geological system" (Ref. 9), bearing broad implications for the field of comparative planetology and thus helping us better understand Earth, other planets and moons in our Solar System, and exoplanets. The three objectives for this goal deal with crustal geologic processes, Mars' interior, and its moons, Phobos and Deimos. Numerous missions have

been flown to Mars with the intention of studying surface geologic processes. For example, the recent InSight lander carried several geophysical instruments to probe Mars' interior (Ref. 12). Several of the investigations that MEPAG identifies under this goal could be well-suited to the flight and hover capabilities of rotorcraft, including mapping the lateral extent of midlatitude ice, stratigraphy of both icy and rocky outcrops, and producing higher resolution global and regional geologic maps.

The fourth and final goal focuses on the future of human exploration on Mars. There is a need for extensive research to be done to ensure that we can safely land, explore, and utilize resources on Mars, while maintaining stringent planetary and astronaut protection protocols. There is an additional objective to explore the surface of Mars' two moons. Fairly extensive atmospheric measurements are needed in order to ensure that entry, descent, and landing (EDL) for a manned mission is safe. A crewed mission would be heavier than anything we have previously sent to Mars, and the acceptable level of risk would need to be lowered. Potentially, rotorcraft could make some of these atmospheric measurements, and could also be useful in mapping of ice and mineral resources, as well as scouting for potential landing or exploration sites.

***Overview of Science Instruments Uniquely Suited for Rotorcraft- and Robotic-Arm-Enabled Missions***

Many different types of scientific instruments have been sent to Mars and elsewhere in the Solar System. With each new lander or rover mission, instrument designs are improved or new instruments are configured for spaceflight. For example, the first Raman spectrometer on Mars, SHERLOC, was a part of Perseverance's science payload, and another will be launched aboard the Rosalind Franklin Rover in 2022 (Refs. 13, 14). In considering the scientific justification of a robotic science arm, several instruments that have prior spaceflight heritage are applicable to high-priority Mars science and could benefit from being mounted on a science arm. Discussed here are the following instruments: alpha particle x-ray spectrometers, hand lens imagers, Raman spectrometers, and meteorological instruments.

*Alpha Particle X-Ray Spectrometers*

The mounting of an alpha particle x-ray spectrometer (APXS) on a science arm could be both scientifically valuable and physically feasible for a future rotorcraft vehicle with MSH-level or higher capabilities. An APXS measures the chemical composition of soil and rocks while in contact with the sample, which it irradiates with alpha particles and X-rays from a radioactive source. The resulting X-ray spectrum is used to identify the elements present in the sample. APXS have proven extremely useful on Martian rovers, allowing the chemical makeup of rocks and soils at four different landing sites to be studied and compared (e.g. Refs. 15, 16, 17). They have provided insights into various surface processes including weathering, aqueous alteration, and ancient depositional environments, benefiting numerous MEPAG objectives spanning all four MEPAG goals. The close proximity the sensor must be to the sample necessitates the source and sensor to be mounted on a science arm that is capable of positioning the sensor head precisely; this is demonstrated in Fig. 3, which shows Curiosity's APXS being deployed. The first APXS launched to Mars was carried aboard the Sojourner Rover, and it was mounted on a small but highly maneuverable science arm. Somewhat analogous to Ingenuity and Perseverance, Sojourner was carried aboard the Pathfinder lander and demonstrated the power of rovers on Mars for the first time. Sojourner's APXS head was mounted on a short but highly articulated science arm, which was able to safely hold the delicate sensor extremely close to samples with high precision.



**Figure 3:** Curiosity's arm-mounted APXS taking data while in contact with a sample. Image taken by the left navigational camera on sol 2313. Credit: NASA/JPL-Caltech.

To date, four APXS instruments have been flown to Mars aboard Sojourner, the twin Mars Exploration Rovers (MERs), and Mars Science Laboratory (MSL). With each new launch of an APXS to Mars, the design has been improved for higher sensitivities (Ref. 18). The relatively light weight of an APXS sensor head and electronics makes it well-suited to be flown as part of a rotorcraft payload. The broad usefulness of an APXS could integrate favorably with the ability of a rotorcraft to travel more efficiently and

access more numerous and diverse locations. These attributes have led to the identification of an arm-mounted APXS as a topic of interest for future Mars rotorcraft payload design.

*Hand Lens Imagers*

Similar arguments can be made for "hand lens" cameras, which can be used to take up-close images of targets to study grain size, texture, and mineral structure, similar to the function of a field geologist's hand lens. Examples of this type of instrument include Curiosity's Mars Hand Lens Imager (MAHLI), which is capable of obtaining resolutions on the order of tens of microns per pixel at a working distance as close as 2.1 cm (Ref. 19), and the Mars Exploration Rovers' (MER) Microscopic Imager (MI), which provided monochromatic black-and-white images (Ref. 20). Similar to an APXS, these instruments are typically arm-mounted to facilitate being placed up close or in near-contact with their targets. Doing so without the aid of an arm could put the instrument and thus the vehicle at risk of colliding with the sample.

*Raman Spectrometers*

Raman spectroscopy is a technique that has only recently been applied to in-situ planetary surface investigations (Ref. 13), but it has been identified as a promising instrument for future missions to Mars and other Solar System bodies (Refs. 21, 22). In a Raman system, a laser is used to probe a sample. A small portion of the laser light interacts with the sample via Raman scattering, and its frequency is shifted depending on the vibrational modes of the molecules in the sample. Analysis of this scattered light allows determination of the chemical composition of the sample. On the surface of Mars, Raman spectroscopy can determine mineralogy, water content and alteration of rocks, as well as the presence and identification of organic molecules (Ref. 23). These measurements are particularly vital in fulfilling MEPAG Goal 1, to search for past or extant life on Mars, but could have broader applications to other MEPAG goals.

The Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) instrument, sent to Mars aboard Perseverance, was the first Raman instrument to land on another planet. It is located on the "hand" of Perseverance's robotic arm, so it can be positioned approximately two inches in front of the sample to be evaluated (Ref. 24). Another Raman instrument is planned for the Rosalind Franklin rover. This instrument will be housed in the rover's interior and will analyze samples taken with the rover's 2-meter drill (Ref. 14). Both of these instruments are the results of significant miniaturization efforts for Raman spectrometers (e.g., Ref. 25). However, in order to fly such an instrument aboard a rotorcraft, further miniaturization is required, as SHERLOC's total weight at 4.7 kg is near the payload capacity for MSH (Ref. 24). The Standoff Ultra-Compact micro-Raman (SUCR) is a recently developed standoff Raman spectrometer that could hold promise for future Mars rotorcraft missions equipped with science arms (Ref. 23). This instrument weighs 4.6 kg, nearly the same as SHERLOC, but it is capable of making measurements at standoff distances on the order of 10-20 cm and takes up a considerably smaller volume. Integration time per line spectrum for a target 20 cm away was found to be 0.1 s (Ref. 23). The fast data collection time as well as standoff target distances could allow for data collection while in a hover while reducing the chance of rotor contact with the sample. Mounting the instrument laser and sensor on a robotic arm could further reduce the risk of rotor blade contact, and it could enable accurate aiming of the instrument's laser and positioning of the spectrograph aperture. The mass of the laser used in testing was 600 g. However, engineering challenges relating to instrument mass and volume could arise depending on which instrument components must be mounted on the arm. If these challenges can be overcome, the flexibility in movement provided by a rotorcraft could pair powerfully with the capabilities of a standoff Raman spectrometer.

*Atmospheric Instruments*

Meteorological measurements were among the first to have been taken at the surface of Mars, with the twin Viking landers each capable of measuring temperature, pressure, humidity, and wind speed and direction at their respective landing sites. These measurements, and the numerous ones taken by the landers and rovers that came after Viking, have been vital to elucidate the atmospheric conditions at Mars' surface. To date, these measurements have only been taken at the landing and science operations sites of the surface missions, so their spatial resolution remains extremely spotty and inconsistent. Some have also provided insight into the conditions higher up in the atmosphere; for example, the Phoenix lander used a LIDAR-based instrument to measure atmospheric dust and clouds at heights up to around 20 km (Ref. 26). Atmospheric measurements are important for understanding Mars' current climate, knowledge of which is vital for any future human explorers. Knowledge of atmospheric dust is particularly useful when planning any solar-powered mission. As such, atmospheric measurements bear particular significance to MEPAG Goal 4 as well as to Goal 2.

A rotorcraft could be a good candidate vehicle for high-quality weather measurements with high spatial and temporal resolution due to their efficiency in travel and

vertical flight ability. They could improve understanding of Mars' planetary boundary layer (Ref. 6). Individual weather instruments tend to be relatively small and lightweight; miniaturization efforts could reduce their size even more (e.g. Ref. 28). Instruments to measure surface conditions are typically mounted on arms, masts, or booms in order to isolate the instruments from aerodynamic and thermal effects of the landers or rovers (e.g. Refs. 27, 28). If a rotorcraft such as MSH were to be flown carrying an atmospheric science payload, care would be necessary to isolate the instruments from the rotorcraft's thermal effects and, in particular, the airflow from its rotors when in flight or hover. Mounting the payload on the end of a long boom or arm could mitigate these issues, although further research would be necessary to determine whether performing atmospheric measurements while in the air may be a more significant engineering challenge.

***Deployment of Instruments from Rotorcraft using Robotic Arms***

The InSight lander made a fairly novel use of robotic science arms. While typically deployed with instruments such as dust removal tools, spectrographs, and sample collection systems, InSight's arm was the first that was solely dedicated to depositing ground-contact instruments onto the surface (Ref. 29). The Instrument Deployment Arm (IDA) deployed several geophysical instruments, including seismometers and a heat flow probe. Unexpectedly, the heat flow probe was unable to penetrate the ground to the required depth of 5 m. The science team attempted to use the IDA to apply force to the top of the probe to bury it as deeply as possible. Although the probe was ultimately unable to reach a proper depth, the versatility of the IDA was demonstrated (Ref. 30).

To date, the seismometer placed by InSight is the only one on the surface of Mars. Obtaining regional or global seismic datasets from arrays of seismometers could potentially provide valuable information about Mars' interior as well as subsurface resources like water ice or any liquid water, investigations which fall under MEPAG Goals 1 and 3. Multiple seismometers could also triangulate the locations of marsquakes and other seismic events. A network of gravimeters on Mars' surface could provide complimentary geophysical information. Ultra-compact micro-electromechanical (MEMS) accelerometers, used in applications ranging from smartphones to Mars rover navigation systems, are sensitive to seismic activity and to gravitational field anomalies (e.g. Refs. 31, 32). Work is being carried out to develop MEMS devices for planetary surface gravimetry and seismology with more favorable sensitivities and noise levels (e.g. Ref. 32). These devices could be lightweight enough, perhaps on the order of several mg, for a rotorcraft equipped with an instrument deployment arm to deposit a regional network of seismometers or gravimeters.

Finally, rocks on the surface of Mars are covered by a thin layer of fine dust particles, the result of billions of years of surface weathering and redistribution under low gravity and dry conditions. This dust covering, with typical thicknesses on the order of microns, can strongly influence contact and remote sensing observations. APXS measurements can be difficult to accurately interpret if this dust is not removed (Ref. 33). Dust can also interact with the surface of rocks to, alongside oxidation, contribute to the formation of alteration rinds on the surfaces of rocks, which also conceals the true interior composition of samples (Ref. 34). Following the Pathfinder mission, which included an APXS on the Sojourner rover but did not include any instruments to remove dust or altered outer surfaces, the Mars Exploration Rovers Spirit and Opportunity included a Rock Abrasion Tool (RAT) to grind away and remove the outer 5mm of rocks for close investigation (Ref. 35). Subsequent rovers have also possessed similar instruments, such as the Dust Removal Tool (DRT) on Curiosity (Ref. 36).

If a future rotorcraft, such as MSH, were equipped with an instrument to analyze the compositions of surface rocks, it would require a tool to remove dust. It could also benefit from an abrasion tool that can further remove outer alteration rinds. There is the potential that the rotors could be spun up with negative collective in order to blow away dust on smaller samples next to the landed vehicle, but more research is required to determine the efficacy of this dust removal method. Furthermore, this method may not work for larger boulders that cannot fit safely beneath the rotors.

**Table 1:** Various previously-flown (with the exception of SUCR) examples of instruments with significant science potential to be mounted on a robotic arm on a rotorcraft such as MSH. Some instrument parameters retrieved from www.mars.nasa.gov.

| Instrument Name, Mission, Year Landed | Instrument Type | Observables or Use | Mass (kg) | Volume ($cm^3$) | Power Consumption (W) | Reference |
|---|---|---|---|---|---|---|
| APXS, Sojourner, 1997 | APXS (sensor head) | In-situ elemental composition of targets | 0.6 | 170 | 0.4 | Ref. (37) |
| SUCR | Standoff Raman Spectrometer | Remote sensing of molecular composition of targets | 4.6 | 2400 | 43.5 | Ref. (23) |
| REMS, Curiosity, 2012 | Atmospheric Suite | Temperature, pressure, humidity, wind speed, UV radiation | 1.24 | 2800 | 0.4 - 10.1 | Ref. (28) |
| RAT, MERs, 2004 | Dust Remover | Removal of dust, abrasion of outer surface of samples | 0.687 | 730 | 8 – 11 | Ref. (35) |
| MI, MERs, 2004 | Hand Lens Imager | Up-close images of mineral grains and texture | 0.29 | 100 | 2.5 - 4.3 | Ref. (20) |

## MSH-RA Engineering Feasibility

After assessing the scientific justification of a robotic arm on Mars rotorcraft, the engineering feasibility of developing such a capability will now be considered. To begin, there was an analysis of previous robotic arms used on the Martian surface. This analysis could lead to a discussion of the constraints and requirements of a robotic arm on rotorcraft.

### *Previous Engineering Examples of Mars Robotic Arms*

In terms of Martian activity, robotic arms have been used on landers and rovers. An example of a lander and rover combination was the Mars Surveyor 2001 Lander discussed in Ref. 38. Although the mission was ultimately canceled, the primary purpose of the robotic arm in this scenario was to support science instruments by digging, taking samples, and positioning the rover (Ref. 38). The Mars Surveyor 2001 robotic arm was a 4-degree of freedom (DOF) manipulator with numerous capabilities. This arm allowed motion about the shoulder yaw and elbow, and wrist

pitch. The tools at the effector consisted of a scoop (digging and sample acquisition), blades (scraping), an electrometer (charge and atmospheric ionization measurement), and a crowfoot (rover deployment). Additionally, the joint actuators consisted of DC motors that could allow the arm to produce around 80 N of force. Finally, the arm had a 2 meter radius of reach and a mass of 5 kg.

Another example of a robotic science arm utilized on Mars is the Mars Exploration Rovers (MER) mission (Ref. 39). In this mission, the twin rovers Spirit and Opportunity were landed on Mars to achieve exploration objectives. Like the Mars Surveyor 2001 robotic arm, the robotic arms on the twin rovers carried suites of instruments to perform various tasks. Each robotic arm had 5 DOF and showcased instruments such as spectrometers, abrasion tools, and imagers (Ref. 39). Each tool could rotate at the arm effector like a turret.

There has been some past work, prior to this paper, that considered the use of robotic arms (Ref. 2) and robotic legs for Mars rotorcraft (Fig. 4). Additionally, there has been research into robotic legs for rotorcraft for terrestrial applications (e.g. Ref. 40). In addition to robotic arms or legs, a wide range of sensors, probes/devices, and semi-independent robotic systems have been proposed to be deployed from Mars rotorcraft and other planetary aerial vehicles (Refs. 3-4).

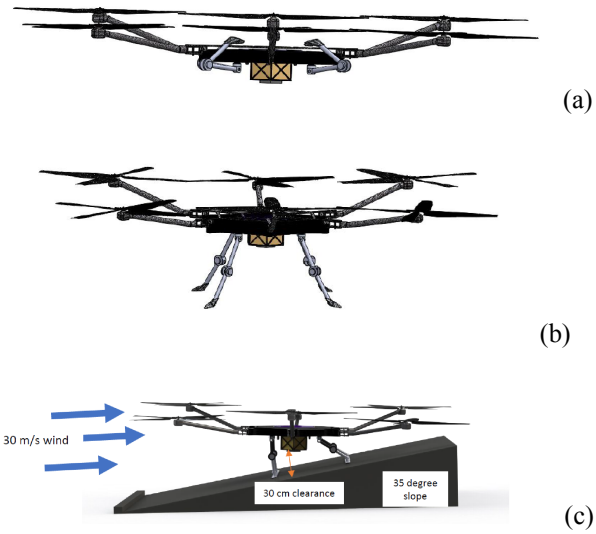



**Figure 4:** Robotic landing legs for Mars Rotorcraft (Image courtesy of A. Chan and A. Tuano: (a) legs stowed during flight, (b) legs deployed on even ground, and (c) legs deployed on uneven terrain.

## Design Requirements of Robotic Science Arm

Design of a successful robotic arm demands the following considerations: the range of motion required, the force/torque requirements, the precision of motion required, and the (self- and external-) collision requirements.

Additional technical challenges arise for robotic arms integrated onto Mars rotorcraft if the arm is required to swap out science instruments/sensors (for example, from a payload bay or instrument carousel) on a periodic basis during arm operation and scientific investigations. Examples of development technical challenges include performing an instrument swap or measurement during active flight.

## Technical Challenges for the Development of Integrated Arm/Vehicle

The key technical challenges for the successful integration of a robotic arm with an aerial vehicle platform can be separated into two major categories: first, those requirements that need to be imposed during flight and, second, those requirements that need to be imposed when on the ground. The key integration requirement during flight is whether or not the arm needs to be operated or actuated in flight. If on the ground, it must be known if ground effects will interact with instruments.

Just as there are overall deployment challenges of a Mars rotorcraft from its EDL aeroshell, there also will be stowing and deploying issues for an integrated robotic arm with respect to the rotorcraft platform. The arm must be of appropriate size and weight to stow /deploy during EDL or conformally stow into a rest position during level forward flight of the rotorcraft.

## Some Preliminary Development Work

The current effort described is still primarily at the conceptual level. Accordingly, the objective of the following MSH-RA design and development discussion is not to discuss a single selected reference (point) design, but rather to provide insight into the key parametric design considerations necessary to one day develop such a reference design. This is necessary because the Mars Science Helicopter platform itself is still an evolving design responding to an evolving mission.

### *Vehicle Mechanical Design Options*

The development of successful Mars rotorcraft demands the use of ultra lightweight structures and electromechanical systems. The addition of a robotic arm adds weight to the overall vehicle. However, it is not merely the weight of the robotic arm itself that is a key concern in MSH-RA development. It is the added weight to incorporate robust interface and adaptor structures to mount/support the robot arm to the vehicle (to resist both arm gravity and actuation loads as well as aerodynamic loads in flight), the extra power and controls to operate the arm, and finally, the need for shifting and mounting/supporting rotorcraft components (such as batteries) to act as counterweights to statically and dynamically balance the loads on the robot arm (and that attendant stiffening of the vehicle structure to mound/support the counterweight to the vehicle).

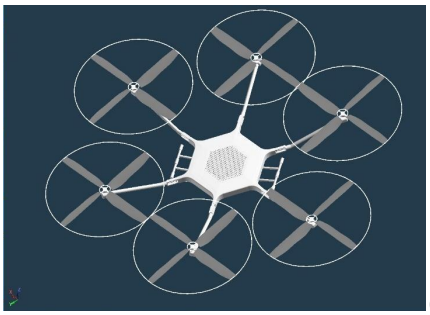
### *Robotic Arm and Science Instrument Integration Design Options*

Looking at previous robotic arms, there are key aspects that define their design. There is the length of the arm, including the length of each arm section. Then, the joints define the ways the arm can move and rotate. Referring to the discussion on constraints, another key aspect is the way the arm stows itself. Finally, the materials should be considered to minimize mass and cost while maximizing strength.

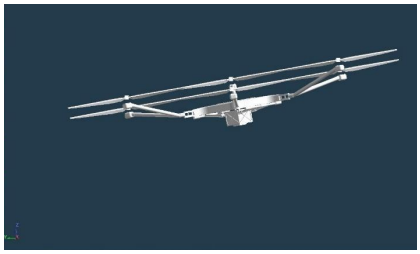
To best describe the potential arm configurations, the methods of attachment, and their respective advantages and disadvantages, Table 2 summarizes the various approaches.

**Table 2: Arm Design Configurations**

| Arm Placement | Attachment to Rotorcraft | Pros | Cons |
|---|---|---|---|
| Top of MSH<br>(Refer to Fig. 6) | Fixed/Moving Base | Easy to stow with arms. Potentially more space for instruments. | Could interfere with solar panels. Could interfere with rotor blades without synchronization of blade position relative to arm movement. |
| Bottom of MSH<br>(Refer to Fig. 8) | Fixed/Moving Base | Structurally efficient design: can incorporate arm with bottom payload bay/container. Potentially minimizes the relative size of the arm. Easy to maintain center-of-gravity at the center of the vehicle. | May be more susceptible to dust contamination due to ground effect. |
| Side of MSH<br>(Refer to Fig. 7) | Fixed Base (Might require a 'wrist' actuator) | Easy to stow with arms. Can achieve a more aerodynamic profile during flight. | Limited to one side of rotorcraft. Could be subject to aerodynamic interactions with the rotor wakes. Potentially limited space on the sides of the vehicle to mount the arm. |
| Mounted to landing gear (legs or skids)<br>(e.g. Ref. 2) | | Projects the robot arm further from the center of the vehicle to further out radially than otherwise. | Landing gear/skids may not have structural stiffness or robustness to support arm |
| Mounted to multi-rotor 'cross arms'<br>(Refer to Fig. 9) | Fixed or moving base (if moving base, could use 'inchworm' actuation) | Even number of (smaller) arms could be accommodated. Greater surface area could be reached by arm. | 'Cross-arms' may not have structural stiffness or robustness to support arm |
| Robotic arms could serve dual purpose as robotic landing legs | Fixed | Dual-purpose robotics | Maintaining standing versus tipping stability when using one of four 'legs' as an arm might be challenging. |

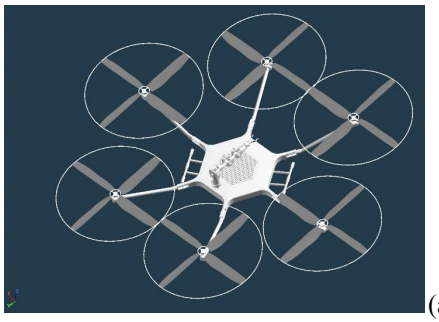


(a)

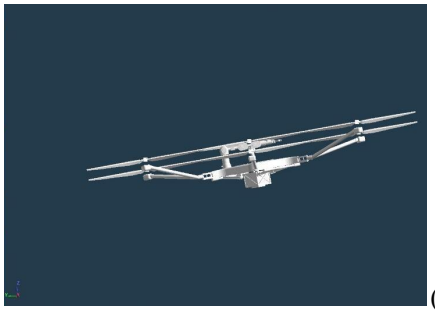


(b)

**Figure 5:** Baseline MSH vehicle (retracted landing skids for forward flight) used for this study: (a) isometric view and (b) side view.

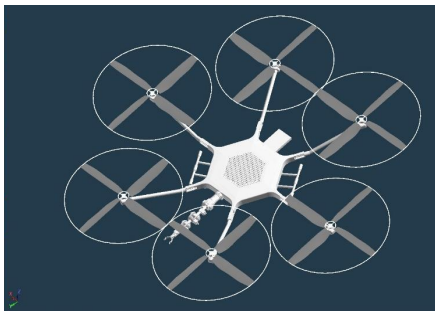


(a)

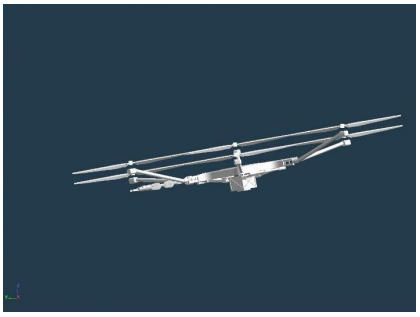


(b)

**Figure 6:** Mounting of Robotic Arm to top of MSH (Config. 1): (a) isometric view and (b) side view.

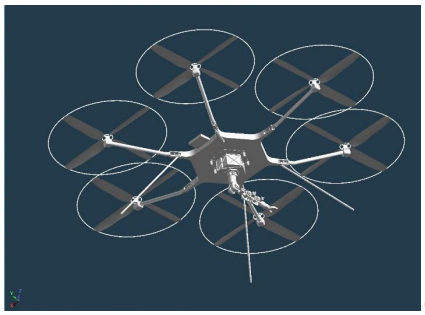


(a)



(b)

**Figure 7:** Mounting of Robotic Arm to Side of MSH (Config. 2): (a) isometric view and (b) side view.



(a)

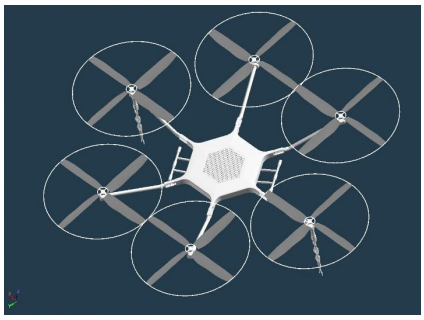


(b)

**Figure 8:** Mounting of Robotic Arm to Bottom of MSH (Config. 3): (a) isometric (bottom) view and (b) side view.

Figure 5 is a set of views of the baseline MSH vehicle used in this study. This design is consistent with the design described in Ref. 7, but does not reflect the larger vehicle that is currently being studied by JPL and NASA Ames.

Figures 6-9 depict a number of the approaches in Table 2 to mounting/integrating robotic arms onto a hexacopter configuration representative of the current design of the Mars Science Helicopter. Four robotic arm configurations, Config. 1-4, are generically depicted. (Note that Ref. 41 is the source of the robot-arm-specific CAD description in Figs. 6-9. This particular robotic arm was selected for this study as it is a well-known and widely-simulated arm model within the robotics community.)



(a)



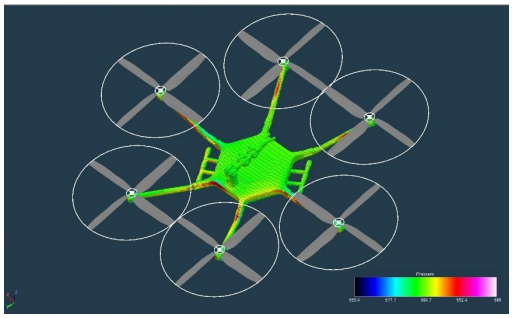
(b)

**Figure 9:** Mounting of Robotic Arm to Cross-Arms of MSH (Config. 4): (a) isometric view and (b) side view.

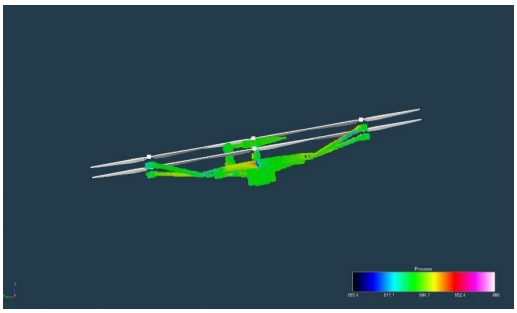
### *Arm and Vehicle Aero-performance Considerations*

As noted earlier, there are novel arm/vehicle aero-performance considerations to the development of MSH-RA. As a part of this work, some initial mid-fidelity computational fluid dynamics predictions (using the CFD software described in Refs. 42-43) were made of the baseline MSH vehicle (Ref. 7) and various identified robotic arm implementations (Table 2 and Figs. 6-9). All arm implementations used scaled CAD model versions of the Ref. 41 arm description; this arm description was chosen because it is a well-known robotic arm model used in the robotics community. Use of the Refs. 39 and 44 robotic arm models will enable easy transition to future robotics simulations of the MSH-RA applications using well-known simulation tools such as Refs. 45-46 and 44.

Figure 10 is a representative surface pressure distribution result for Configurations 1-4. The MSH and robotic arm are characterized predominately by pressure drag rather than viscous drag, primarily because of the aggregate bluff body nature of their physical geometries.



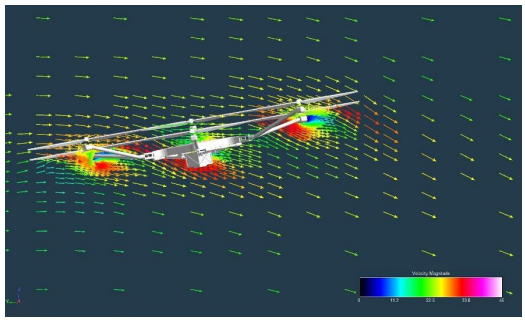
(a)



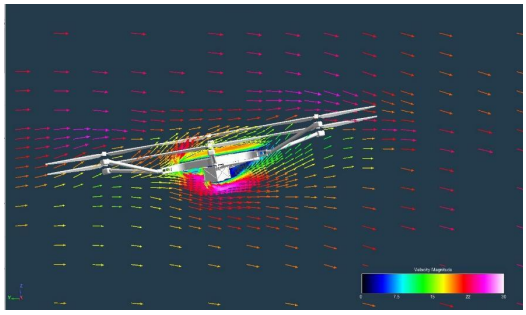
(b)

**Figure 10:** Representative surface pressure distribution result (Config. 1 with landing gear skids retracted and robot arm mounted on top of vehicle): (a) isometric view and (b) side view.

Figures 11-15 are edgewise forward flight CFD predictions of the baseline (no arm) MSH and the four robotic arm configurations, Config. 1-4. In particular, the centerbody x-plane slices through the centerbody lateral plane of symmetry (or, in the case, of Configuration 4, the x-plane goes through the lateral outermost rotor and robotic arm axes) help visualize the larger region of separated flow stemming from the installations of the robotic arms on the vehicle.

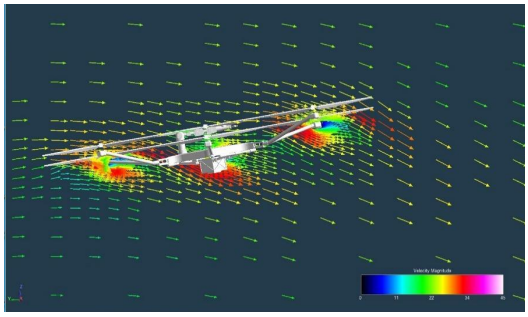


(a)

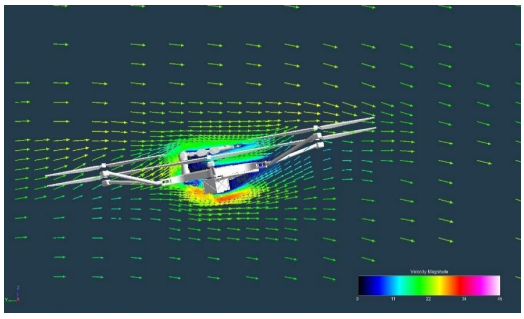


(b)

**Figure 11:** Baseline MSH forward flight: (V=20 m/s , pitch attitude of -10 deg.;untrimmed rotors; constant rotor collective of 15 deg. uniform tip speed of 163 m/s): (a) velocity flow map at two rotor axes and (b) velocity flow map through centerbody.

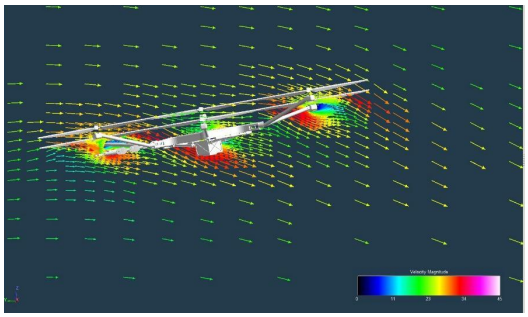


(a)

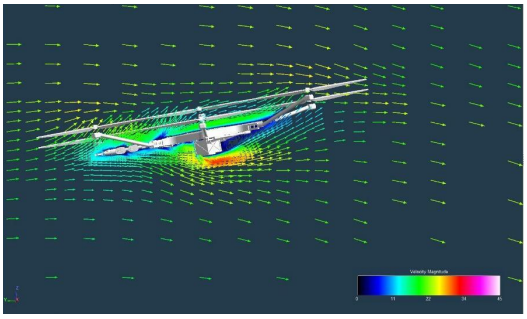


(b)

**Figure 12:** Config. 1 forward flight: (a) vector flow map at two rotor axes and (b) velocity flow map through centerbody.

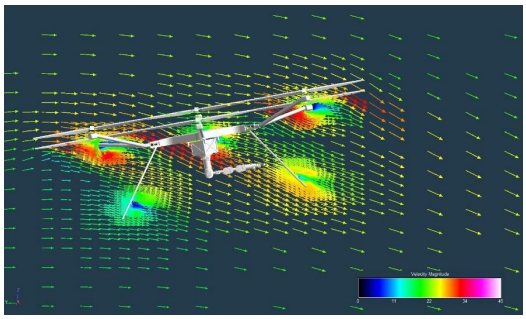


(a)

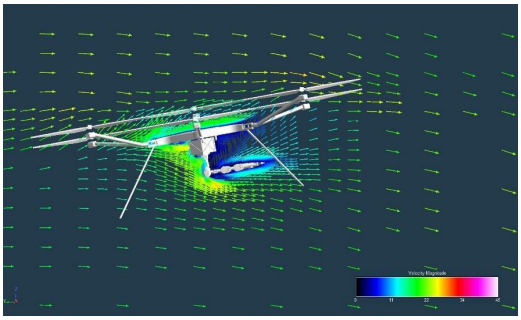


(b)

**Figure 13:** Config. 2 forward flight: (a) velocity flow map at two rotor axes and (b) velocity flow map through centerbody.

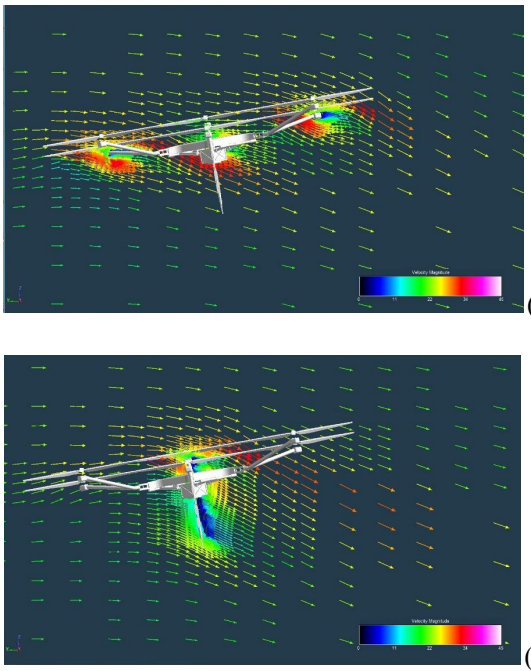


(a)



(b)

**Figure 14:** Config. 3 forward flight: (a) velocity flow map at two rotor axes and (b) velocity flow map through centerbody.



(a)

(b)

**Figure 15:** Configuration 4 edgewise forward flight: (a) velocity vector flow field map at x-plane slice going two rotor axes and (b) vector map for x-plane slice going through the outermost lateral rotor and robotic arm axes.

The forces and moments presented in Figs. 16-18 are all for the same flight/operating condition: a pitch attitude of -10 deg., a forward flight speed of 20 m/s, an atmospheric density of 0.01 kg/m$^3$, and a surface temperature of 214 K, a specific heat constant of 1.29, and an ambient static pressure of 584 pascals. The rotors are all untrimmed and are set at a uniform collective of 15 deg. and a uniform tip speed of 163 m/s. Increased drag is a major concern for the implementation of a robotic arm on an aerial platform. Preliminary mid-fidelity results would suggest that for the MSH application, the drag increase for some of the arm configurations are relatively small and, in some cases, demonstrate less drag than the baseline (no arm) vehicle. For the vehicle download (negative vertical force), there is little difference between the robotic arm integration configurations and the baseline vehicle (a favorable result from a vehicle development perspective). Finally, all configurations see either the same level, or less, of vehicle nose-down pitching-moment as the baseline MSH vehicle. This is a good result from a development perspective. These are mid-fidelity, relatively coarse gridding and time step results. More detailed work with finer gridding and perhaps higher fidelity CFD tools may be performed in the future.

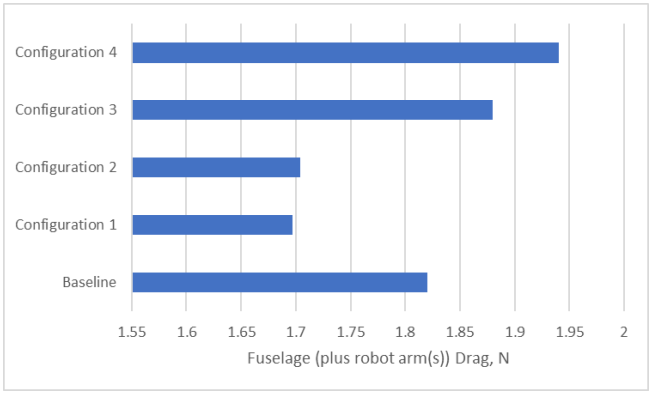



**Figure 16:** Predicted drag force for Configurations 1-4 versus baseline MSH configuration.

The higher drag estimates for Config. 3 and 4 could be moderated by using retractable landing gear for Config. 3 (for its longer legs) and for Config. 4 by actuating or deflecting the two robotic arms such that they were no longer nearly perpendicular to the freestream velocity.

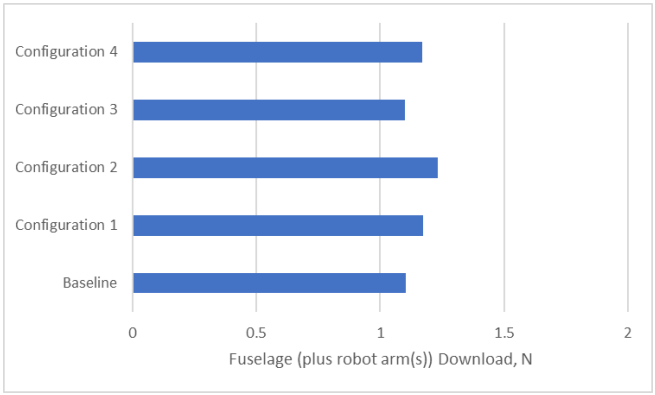



**Figure 17:** Predicted download force for Configurations 1-4 versus baseline MSH configuration.

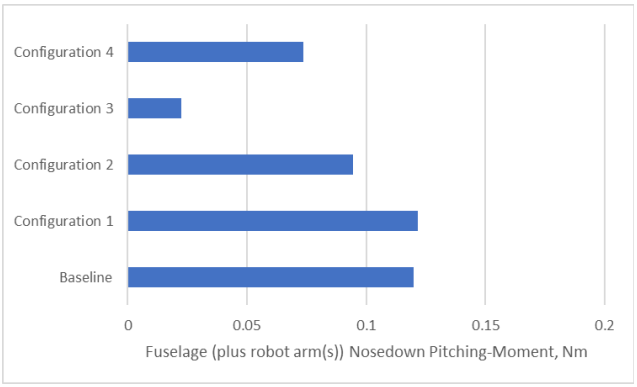



**Figure 18:** Predicted nose-down pitching-moment for Configurations 1-4 versus baseline MSH configuration.

As noted earlier in the science justification portion of the paper, dust and dust-removal are key considerations in acquiring high-quality APXS and Raman spectrometer measurements of rocks on the Martian surface. A novel approach to dust removal may entail using the MSH rotor wakes (with their intrinsic high induced velocities) to blow dust off rocks to be sampled while hovering and landing, or alternatively, added extra dusting by lower than 1 G thrust-levels while the vehicle is sitting on the ground. If proven to be an effective means of dust removal for science instrument measurements, then the overall complexity of the robotic arm would be reduced, as a specially designed dust removal tool would not need to be developed and carried by the aerial vehicle.

One of the issues that could arise during HIGE is that there could be a 'dead air' immediately below the MSH centerbody fuselage. Therefore, rocks directly underneath the centerbody fuselage would unlikely have dust sufficiently removed from them from the rotor wakes. Rocks or other surfaces that would be somewhat horizontally offset from the centerbody vertical axis would see dust removal.

Rotor dust kickup occurs when the rotor wake velocity magnitude exceeds the saltation threshold velocity for the particular dusty surface at the landing site. Ingenuity itself has stirred up dust kickup during takeoff, Ref. 49. As larger vehicles are developed, dust kickup (also known as "brownout") will potentially become a larger problem to overcome.

### *Robotic Arm Simulations*

Development of an MSH-RA will need to be a tightly coordinated effort between aerial vehicle developers and roboticists. As noted earlier, development of MSH-RA will be especially challenging because of mass, power, and structural robustness considerations. Accordingly, bringing robotics expertise early into the vehicle development, even at the conceptual design stage, will be required.

A challenging set of vehicle control problems results if the robotic arm is anticipated to be operated during flight of the vehicle. This problem has begun to be explored in the laboratory for terrestrial drone applications (Refs. 47-48) but remains a largely unexplored area of research for Mars rotorcraft and other planetary aerial vehicles.

The key robotics technical challenges for MSH-RA are vision-processing (both when in the air and on the ground) to identify targets/rocks of interest, collision-avoidance software able to keep the arm colliding with rotorcraft structures, particularly the landing legs, software to account for center-of-gravity shifting with arm movement to identify and avoid hazardous arm movements, and fail-safe software to seamlessly switch between flight mode and on-the-ground science mode. To assess possible solutions to these robotics technical challenges, it will require an extensive amount of robotic arm simulations – simulated as being mounted to an aerial platform and operating in a Mars-like surface interactive environment. Performing such extensive simulations is beyond the scope of the current paper. Some preliminary work has begun in this area, however, shown in Fig. 19.

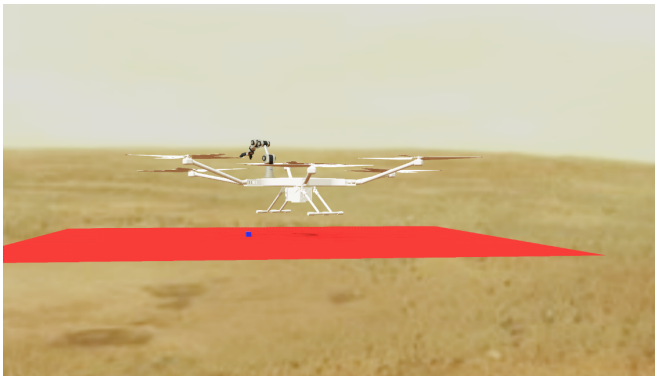


**Figure 19:** Initial robotics simulation modeling (single still frame from simulation movie) using Ref. 44 simulation tool and provided robotic arm model.

## Technology Roadmap and Future Work Needed

Fig. 20 illustrates a possible technology roadmap over the next few years as to potentially readying the technology necessary for a future MSH-RA mission. Though a fair amount of laboratory work has been conducted on terrestrial applications merging robotic arms, legs, and other devices with flying drones, very limited field work has been conducted. To achieve realizable demonstrations of the capabilities that MSH-RA might present for future NASA missions, it will be necessary to conduct field science campaigns of surrogate vehicle and robotic arm systems at Mars-analog sites.

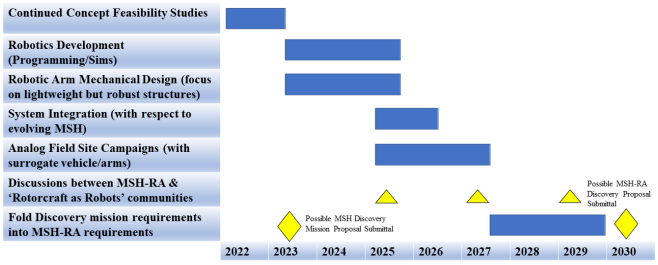



**Figure 20:** Possible MSH-RA Technology Roadmap.

## Concluding Remarks

Leveraging the ongoing conceptual design efforts towards the potential development of a next-generation Mars rotorcraft beyond Ingenuity, a surface interactive variant of the Mars Science Helicopter is proposed to integrate a robotic science arm into its aerial platform. This variant is referred to as MSH-RA. The advantages for incorporating such a robotic arm into an aerial vehicle are discussed in terms of enhancing the mission capability of Mars rotorcraft to address compelling science questions that are not addressable in any other way.

Notional mission and design requirements for MSH-RA are identified. Key technical challenges for the development and usage of such vehicles are also identified. Finally, the preliminary work performed to date has been described, and future work to full realization of the concept has been outlined.

Author contacts: Cole Rutter rutterce@mail.uc.edu
Mackenzie Lach mrlach@uci.edu

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