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## ENABLING THE CAPTURE AND SHARING OF NASA TECHNICAL EXPERTISE THROUGH COMMUNITIES OF PRACTICE

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Historically, engineers at the National Aeronautics and Space Administration (NASA) had few opportunities or incentives to share their technical expertise across the Agency. Its center- and project- focused culture often meant that knowledge never left organizational and geographic boundaries. With increasingly complex missions, the closeout of the Shuttle Program, and a new generation entering the workforce, developing a knowledge sharing culture became critical. To address this need, the Office of the Chief Engineer established communities of practice on the NASA Engineering Network. These communities were strategically aligned with NASA's core competencies in such disciplines as avionics, flight mechanics, life support, propulsion, structures, loads and dynamics, human factors, and guidance, navigation, and control. This paper describes the process used to identify and develop communities, from establishing simple websites that compiled discipline-specific resources to fostering a knowledge-sharing environment through collaborative and interactive technologies. It includes qualitative evidence of improved availability and transfer of knowledge. It focuses on pivotal capabilities that increased knowledge exchange such as a custom-made Ask An Expert system, community contact lists, publication of key resources, and submission forms that allowed any user to propose content for the sites. It discusses the peer relationships that developed through the communities and the leadership and infrastructure that made them possible.

### I. INTRODUCTION

While often seen as one entity, the National Aeronautics and Space Administration (NASA) is actually made up of ten field centers that are geographically distributed across the United States. Each of these centers evolved with its own culture and identity, some before NASA was formed as an agency. These identities in many ways are based upon their differing purposes. Some are research labs, some are robotic space flight centers, and some are human space flight centers. For the most part, until very recently, work was done exclusively within the center and collaboration across centers was less frequent. All of this has resulted in each center having its own unique culture, and little or no need to interact with other centers other than on the occasional project. Most knowledge stayed within the center and never rose to an Agency level. In addition, some centers preferred to keep knowledge restricted because they were competing with each other for projects and funding. After the Space Shuttle Columbia accident and the new vision for NASA, it was clear this would have to change. [1]

In 2004 when President George W. Bush announced the Vision for Space Exploration, this included a

mandate that the Shuttle Program be retired in 2010 and replaced with a new crew and cargo vehicle that could travel farther than near-Earth orbit. The effort to design and build a new set of launch and spacefaring vehicles was large enough that it required cross-center collaboration and comparable expertise and skill sets amongst its engineers. It quickly became clear that knowledge sharing would play a vital role in this collaboration and in ensuring that NASA could continue developing innovative technologies. Although the Constellation Program that was building this new set of vehicles was canceled, the Orion crewed spacecraft is still being developed. In addition, the bold suggestions of the Augustine Commission would not be feasible without a unified NASA. [2]

Technical innovation was not the only challenge facing NASA at this time. Its workforce was aging, and the gap between the incoming younger generation and the generation nearing retirement was growing. As with most organizations, there was concern about the loss of institutional memory, but of even greater concern was that there were not enough engineers in a broad range of career levels to meet the challenges of newer and more complex missions. In Fiscal Year 2010, the average age

of NASA civil servants was 47. There were 3 times more people over-60 than under-30 at NASA in certain job classifications. [3] In engineering, the changing demographic is alarming. According to the U.S. Government Accounting Office, if the workforce continues aging, not enough engineers will have moved up the ranks in time to acquire the requisite technical and leadership skills to enable NASA to meet its vision for space exploration. [4]

In response to these problems, NASA's Office of the Chief Engineer (OCE) established communities of practice on the NASA Engineering Network (NEN). NEN is a suite of information retrieval and knowledge-sharing tools specifically aimed at facilitating communication among the technical workforce at all NASA centers. The network provides access to the official lessons learned system, case studies, organization charts, a cross-repository search, and communities of practice.

## II. COMMUNITIES OF PRACTICE

### Definition

On NEN, a community of practice (CoP) is a group of people "who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis." [5] By deepening their own knowledge, they are able to improve the performance of an organization as a whole. Communities have existed throughout history, through organizations such as guilds and professional societies like AIAA, ASME, and IEEE, but until recently they were not formally and strategically established within the aerospace industry. Communities of practice not only are an effective means for capturing, sharing, and using knowledge, but also provide a means for collaboration and innovation. They have become a more prevalent component of knowledge management strategies and many major organizations. [6] Communities focus on connecting the workforce across organizations, projects, geographies, and functions, exactly what NASA was seeking. [7]

A note on terminology: A community of practice is a group of people with a shared interest who engage with each other to solve problems, learn, or innovate. The term is often used synonymously with technology that supports this interaction; on NEN that means online sites. For this paper, we have tried to clearly indicate when we are referring to the community of practice sites or the community of practitioners looking to improve NASA's capabilities and skill sets.

### Strategic Communities of Practice

Because NASA had a mission to improve its performance after the Columbia failure, communities were strategically aligned with the Agency's core competencies. These core competencies, 19 in all, are

system-level disciplines such as propulsion, human factors, avionics, and guidance, navigation and control. See Table 1 for a list of communities of practice on NEN.

NASA Engineering Communities of Practice
Aerosciences
Autonomous Rendezvous & Docking
Avionics
Electrical Power
Environmental Test & Verification*
Fault Management*
Flight Mechanics
Guidance, Navigation & Control (GN&C)
Human Factors
Life Support/Active Thermal
Materials
Mechanical Systems
Nondestructive Evaluation
Passive Thermal
Propulsion
Software
Structures
Systems Engineering*

\* Leaders are not Technical Fellows

Table 1: NASA Communities of Practice

### Community Leadership

A few years before NEN was founded, then-Administrator Sean O'Keefe formed the NASA Engineering and Safety Center (NESC) with the purpose of providing a central location to coordinate and conduct robust, independent engineering and safety assessments across the Agency.

At the core of the NESC is an established knowledge base of technical specialists pulled from the ten NASA centers and from a group of partner organizations external to the Agency. This ready group of engineering experts is organized into discipline areas called Technical Discipline Teams (TDTs). TDT members are drawn from NASA, industry, academia, and other government agencies. By drawing on the minds of leading engineers from across the country, the NESC consistently solves technical problems, deepens its knowledge base, strengthens its technical capabilities, and broadens its perspectives, thereby further executing its commitment to engineering excellence.

The NESC TDTs have a demonstrated ability to bring the cognitive diversity of their technical talent to bear on multiple high priority problems within NASA and have collectively become a very valuable resource to senior Agency decision makers. [8].

NESC then started a NASA Technical Fellow program. These Technical Fellows assemble, maintain and provide leadership for the TDTs and are stewards for their disciplines. They serve as the senior technical

experts for the Agency in support of the Office of the Chief Engineer and the NESC. They are an independent resource to the Agency and industry to resolve complex issues in their respective discipline areas. [9]

NESC, in particular the NASA Technical Fellows, also serve to break down any technical communications barriers between the engineering organizations at NASA's centers with the objective of stimulating cross-Agency sharing of experiences and expertise, modelling and simulation tools, analytical methods, design and test facilities, etc.

When it came time for NEN to identify champions to lead the technical communities of practice, NESC and its Technical Fellows provided a perfect match. In those few cases where a Technical Fellow was not in place, the OCE identified leaders from other areas. For example, the head of the Agency-wide Systems Engineering Working Group became leader of the Systems Engineering community of practice.

### Online Presence

Due to the geographically distributed nature of NASA, communities required an online presence that would be open to all personnel behind the firewall. In addition, many of the core competencies have hundreds of practitioners so routine face-to-face or teleconference meetings were simply not feasible. The online sites would have to become the gathering point for these practitioners.

It was also important that each of the community sites have a consistent look and feel. As a result, the color scheme, navigation and layout are all preset by the NEN team. One example of this standardization is that each site is required to have a picture and biography of the leader on the home page. This area welcomes users, explains the purpose of the community, and infers the authoritative content through the Technical Fellow's leadership. See Figure 1 for a sample community home page.

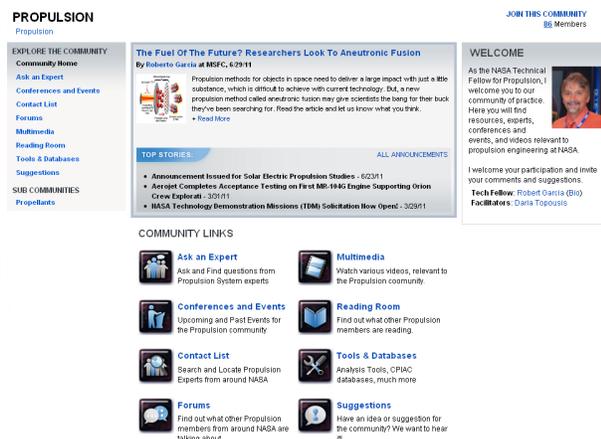


Figure 1: Sample Community Home Page - Propulsion

While the sites are led by the Technical Fellow, the communities themselves are meant to be non-hierarchical. Any user should feel comfortable asking questions, suggesting content, or admitting they have gaps in their knowledge. This follows industry best practices. [10]

The leaders and their team work hard to ensure that content is fresh and of value to the community. Otherwise, the sites would not be used. If the content were not interesting or regularly updated, engineers who visited once would not have incentive to return. To address this, each community has a news area on its home page that is regularly updated. In addition, newsletters are distributed periodically via email to notify users of updates to the sites.

These online sites allow engineers to asynchronously interact, which makes it easier for people who need more time to think, review, and participate on their own timeframe. [11] This is particularly good for the busy technical workforce, especially one that is working in different time zones. An engineer can respond to an online discussion, pose a question, and interact with peers when he or she has the time and not worry that the other person may be offline at that moment. This also enables engineers to interact with people they may never have met before, allowing new relationships to form.

### Establishing a New Community

Because the communities were strategically chosen by the OCE, the NEN team had a predetermined list of which sites to build. The team approached the most amenable Technical Fellows first, and worked to convince them to just collect content and put it on the sites. At that time, in 2006-2008, there were few websites with a discipline-specific focus and definitely none at the Agency level, so putting a website that provided content was a big step for NASA. This would also involve a culture change by the engineers; they would have to learn to use NASA-wide sites to find information and expertise online versus depending on organization-specific networks. Once this change was made, the sites could evolve into true communities that focused on participation and input from their members.

Each community site has a facilitator, who is a member of the NEN team. This person is versed in theory and practice, and works with the Technical Fellow and his or her team to determine the right kinds of content to put on the site. While the site is being built, the facilitator has regular meetings with the team, preferably once per week until the site goes live. The site remains hidden to users until the team feels there is enough content to draw users in and give them reason to return.

In most cases, the facilitator attended NESC Technical Discipline Team teleconference meetings to

listen for problems the engineers were having to see where the community site might meet their needs. The facilitator also attended the annual TDT face-to-face meetings held by the Technical Fellow to not only listen for content but to start building relationships with community members, so they would feel comfortable sending ideas to the facilitator. These personal relationships were key to establishing new community sites.

Most communities chose to have one centralized site that compiled information from varying sub-disciplines. The Flight Mechanics site, for example, has one page of best practices that is broken into sections such as EDL, parachutes, and flight mechanics fundamentals. The Avionics Technical Fellow, however, decided that his community would be best served by being broken into sub-discipline sites within the main Avionics CoP. An engineer can find facilities and conferences related to all of avionics, or dive into a sub-community such as EEE parts or Programmable Logic Devices to find specific resources and interact with peers also working in that field. While participation in most communities is not specifically funded, the lead of each of these sub-disciplines in Avionics has a charge number that allows him or her to host regular teleconferences, update content on the site, and interact with the community. This allows practitioners to focus on their specific area of interest. To date, Avionics has four live sub-communities with two in development and more planned for the near future.

### Challenges

Setting up new communities and encouraging members to participate has not been an easy task. Engineers are oversubscribed with project work, so asking them to spend time online was difficult. The community leads and facilitators worked to engage younger engineers who might be eager to interact online with mixed results.

The lack of a face-to-face or catalyzing event/deliverable also made it difficult to get engineers to coalesce as a community across geographical boundaries. As mentioned previously, without an engaged community that contributes new content, the sites can become stagnant. To mitigate this problem, the facilitators have worked to comb news stories, monitor email traffic and personally encourage people to participate.

Another challenge to getting traction with the communities has been due to lack of communication. Travel funds are limited, so while visiting every center to give CoP site demonstrations and encourage participation has been a goal, it has been a slow process. One positive activity that happened independently of the facilitators or Technical Fellows was the word-of-mouth that occurred on Yammer. Yammer has recently gained

a foothold at NASA as a means of having quick conversations with peers and finding out about the latest happenings, much like Twitter. Through monitoring of Yammer feeds, it was seen that engineers were having conversations about discovering NEN and the communities. In parallel with these Yammer threads, the community sites experienced spikes in page hits and subscription.

### Interactive Content

The NEN team has implemented several technologies to facilitate the transition from website to true communities with interactive content. The system was upgraded to Liferay, an open source portal platform that provided many out-of-the box Web 2.0 capabilities such as blogs, discussion forums, and wikis.

In addition, the team developed an Ask an Expert system that allows users to pose question to vetted experts. These questions and answers are captured and stored online so others can benefit from them. The APQC, a leading process improvement organization, validates NASA's approach of involving experts in communities so that members "can benefit from their invaluable experience." [12]

The team also developed and implemented "Join This Community." This allows engineers to align themselves with a community, indicate their area of interest, and appear on the contact list. Any user can then find engineers based on their area of interest by filtering on sub-disciplines. This has been a major step forward in focusing on the people part of the community. See Figure 2 for an example of the GN&C member list filtered according to people interesting in "Launch Vehicle GN&C." Members also receive monthly updates that indicate the latest changes to the site. Community success is now measured in part by number of members.

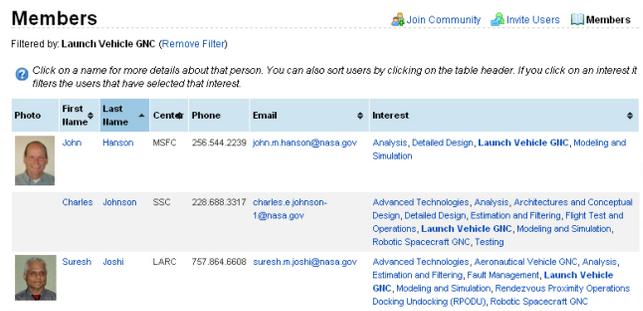


Photo	First Name	Last Name	Center	Phone	Email	Interest
	John	Hanson	MSFC	256.544.2239	john.m.hanson@nasa.gov	Analysis, Detailed Design, Launch Vehicle GNC, Modeling and Simulation
	Charles	Johnson	SSC	228.688.3317	charles.e.johnson-1@nasa.gov	Advanced Technologies, Analysis, Architectures and Conceptual Design, Detailed Design, Estimation and Filtering, Flight Test and Operations, Launch Vehicle GNC, Modeling and Simulation, Robotic Spacecraft GNC, Testing
	Suresh	Joshi	LARC	757.864.6608	suresh.m.joshi@nasa.gov	Advanced Technologies, Aeronautical Vehicle GNC, Analysis, Estimation and Filtering, Fault Management, Launch Vehicle GNC, Modeling and Simulation, Rendezvous Proximity Operations, Docking Undocking (RPDOU), Robotic Spacecraft GNC

Figure 2: Membership list filtered by area of interest

The next set of changes to communities will include implementing a workflow that allows engineers to propose new content or changes to existing content and a taxonomy that will make information more easily discoverable.

### III. EXCHANGE OF TECHNICAL EXPERTISE

#### Methodology

To evaluate the efficacy of communities of practice, several measurements are used. Page hit counts are collected each month. These provide a quantitative measure of visitors to the sites, but can be misleading. Page hits are collected every time a user visits any area of a community. If for example, a user clicks on the home page, then looks at conferences, then looks at the Ask an Expert system, that interaction counts as three hits. Some communities have more pages than others. Systems Engineering, for example, has many pages, and users are required to click several times to access specific content. By having more pages to click on, one user can drive metrics up and make one community seem more popular than it might in reality be. As a result, page hit metrics are not as reliable a measure of community performance as other metrics.

In order to more broadly and accurately assess community performance, qualitative measurements are used to complement the page hits metric. In April of 2011, a survey was distributed at all the centers that asked engineers what they thought about the communities. The team received 45 responses from a range of practitioners in varying stages of their careers. Respondents were asked what would encourage them to use communities, how they felt about the look and feel of the online sites, what other communities or associations they were affiliated with, and what overall recommendations they would suggest. They generally found the sites easy to use. When asked what would encourage them to return to the communities, most said current content and document repositories. See Figure 3 below for responses. Users also provided suggestions specific to each community. These results were distributed to the community leads.

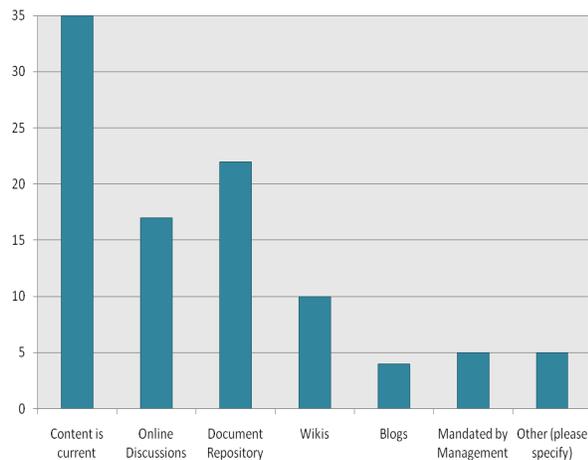


Fig. 3: CoP Survey Results - What would encourage you to use the CoPs?

Other qualitative data was gathered by simply monitoring the sites themselves. The following section describes some of those results.

#### Online Interaction

One of the successes of the communities of practice on NEN has been through the custom-made Ask an Expert system. The system is populated for each discipline with categories and experts vetted by the Technical Fellow. Having categories enables the engineer to have his or her question answered by experts with knowledge in that specific area. These categories are usually aligned with sub-disciplines. For example in the Propulsion community, categories include topics such as electric propulsion, airbreathing, propellant storage, pyrotechnics, and valves and actuators. A user asking a question in the electric propulsion area will only get answers from experts vetted in that sub-discipline.

The system also includes an email component to notify experts when a question has been asked and to notify the questioner that they have received a response. The benefit of this system is that questions and answers are stored online so that other engineers across the Agency can learn from them as well. Long term, this is preferable to a typical email exchange between two parties that is hidden to the rest of the CoP and eventually is lost completely. Figure 4 shows the main landing page for the system.

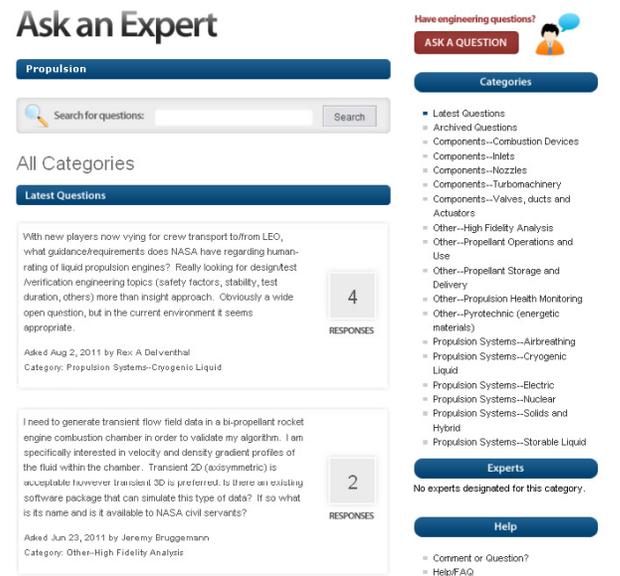


Fig. 4: Screen capture of the Ask an Expert system. Users can see at a glance how many answers a given question has.

Currently five communities are using the Ask an Expert system, two of them with broad success. Questions on Ask an Expert have been asked by users of varying career levels, from summer students to mid-to-late level career engineers. Topics have included questions about which specifications to use, human rating of liquid propulsion engines, and mechanical tests on lunar simulants.

Getting questions on the system was slow at first. The system was launched in October 2009, but the first question was not asked until January of 2010. Since then, 13 questions have been asked with 22 answers from experts. Ask an Expert is a popular feature at live demonstrations, so it is expected that usage will increase as more people become aware of it.

Other communities, instead of or in addition to using the Ask an Expert feature, have developed frequently asked question areas and populated them with questions. The Life Support/Active Thermal community, for example, has an FAQ feature that lists questions collected by the Technical Fellow, a 48-year veteran of NASA, over the span of his career. Questions have been posted about the Lunar Module and Shuttle environmental control and life support systems.

In addition to the Ask an Expert and the FAQ features, some communities have also adopted discussion forums. Unfortunately, these forums have had little to no traction to date. This may be due in part to the culture. NASA users are for the most part accustomed to interacting via email. This problem is not unique to NASA. Other organizations have found that online discussions do not tend to happen until people have built their online networks [13]. Until that happens, users will continue interacting with their existing network via email and other traditional methods.

#### Discovery of People and Organizations

In the survey of NEN users, one of the most touted components of the communities was the contact list. These lists vary from community to community. In some cases it includes members of the NESC Technical Discipline Teams. In others it may be a list of experts the CoP leader has assembled or a list of community members who regularly call into meetings. The contact list has become one way of finding experts for offline conversations. Before the online communities were available, the only way to find fellow practitioners was by contacting people in your known network or contacting a line manager. With the online sites, users can now find experts across all the centers and in multiple sub-disciplines.

One user cited the community as a means for finding two experts in Mechanical Systems, with whom he was able to discuss his research into an alternate means for mirror actuation on a small satellite. The user had little

experience working with piezo motors, but through the site was able to get expert advice from two members of the community. Projects have also used the contact lists to invite users to participate in reviews.

In addition to contact lists for individual practitioners, several of the sites also describe capabilities at different centers in the given discipline. In the Guidance, Navigation & Control community, for example, every center provided a PDF or PowerPoint file describing their GN&C capabilities, recent projects they have been involved in, and facilities available for test and assembly. This has allowed engineers to learn what their peers are doing in different locations, and has enabled some networking and bridging of the community despite geographic boundaries.

#### Access to Key References

As a result of the early efforts by community members to collect and disseminate key references, engineers have been able to benefit from this knowledge. The sites link to best practices, standards, specifications, handbooks, white papers, and other resources that community members have suggested.

In one case, there was a NASA special publication related to propulsion that had been kept by one staff member at Stennis Space Center in Mississippi. Any engineer interested in reviewing this publication would have to track down that one individual, request the hard copy, and return it when finished. When the Propulsion community went live, we were able to post that document online. As a result, engineers across Stennis are now able to download and view their own copy of the document.

In another case, after the Mechanical Systems community went live, one of the Technical Discipline Team members suggested that we create a link to the European Space Agency's standard on mechanisms. Previously, engineers had been unaware that this standard was online through the European Cooperation for Space Standardization site. After posting a link on the Mechanical Systems site, several engineers contacted us to let us know they were very thankful to be able to access this document through the community. A Mechanical Systems group supervisor at the Jet Propulsion Laboratory notified his employees of this link when he discovered it was available.

#### Capture and Distribution of Expert Insight

In some cases, the existence of community of practice sites has provided a forum for experts to share their insight with others.

In the Environmental Test & Verification community, the leader has used the blog capability to share insights on things happening in his field. Recently, for example, he posted a blog summarizing the Aerospace Testing Seminar he attended in Los Angeles.

He shared his notes from the seminar, allowing people across the centers to benefit from his attendance. He plans to use the blog regularly to keep community members up to date with the latest updates in the field.

The leader of the Life Support/Active Thermal community has accumulated a wealth of knowledge over his 48 year career at Johnson Space Center in Houston. When he first started the community, in 2009, he described to his facilitator that he had a career's worth of documents on his computer and in storage. Because he was concerned that this information would evaporate once he retired, he used the document repository to upload documents. To date has loaded almost 100 files related to Apollo, Skylab, Shuttle, the International Space Station, suit ports and locks, and general environmental control and life support systems. Engineers who have reviewed the site, either as part of the NEN feedback survey or through communication activities have indicated that the documents make the site not only relevant but a very useful resource.

Several of the sub-communities within Avionics were able to form specifically because of the CoP capability on NEN. The Electromagnetic Interference (EMI)/Electromagnetic Compatibility (EMC) community had been trying for some time to find a way to connect across the Agency and share key references but had been unable to do so because no forum existed. Once communities of practice were formed as part of NEN, this group of practitioners approached the Technical Fellow to request space. Now the community has a teleconference every other month where practitioners are able to share their experiences with each other. They also have a visible site that raises awareness among engineers working in other disciplines as well. In addition, many engineers working in the field had wanted to attend the EMC Symposium but it was seen as an unnecessary expense. Once the EMI/EMC sub-CoP within Avionics formed, they decided to hold their annual face-to-face in conjunction with the EMC Symposium. Because this face-to-face component was an official NASA meeting, many more engineers were able to go the symposium and learn from their peers. As a result, they were able to network with peers and bring back whatever they learned to NASA.

Another sub-community within Avionics, Wireless Avionics Connections, is set up much like the EMI/EMC community. They meet monthly to discuss the latest issues and to hear community members present on a topic of mutual interest. Soon after forming, the group began to discuss how to mitigate solar flare effects on wireless connections. As part of the regular Wireless Avionics Connections sub-CoP monthly telecon, an expert was invited to present to attendees about that topic. Without a community of practice, there would not have been an Agency-wide forum for sharing this information.

Given the tight schedules and constrained budgets most of NASA's engineers labor under, one of the most pragmatic services a CoP site can provide is access to generic computer-based dynamic models. Having such pre-validated dynamic models available online gives engineers a jump-start in performing their simulation and analysis, especially for early concept development and conducting fundamental system trade studies. The Flight Mechanics CoP has done just that by developing a library of portable dynamic models, all in a common industry standard format useable on most computer platforms/workstations. On the Flight Mechanics CoP site an engineer can pick up and quickly start to use a particular dynamic model, e.g., a routine/script model for modelling launch vehicle propellant slosh dynamics. It is envisioned that additional CoPs, such as the GN&C CoP, will adopt a similar online dynamic model library feature. Furthermore, it is likely that the this CoP functionality will be expanded in the near future to allow engineers to not only be able to pick up a model previously developed by a discipline colleague, but to also be able to drop off validated models they have developed as well. Thus a desirable and valuable two-way peer-to-peer dynamic model exchange system has been established on the Flight Mechanics CoP site.

#### IV. CROSS-DISCIPLINE COMMUNITIES

##### The NASA Autonomous Rendezvous and Docking (AR&D) Community of Practice

The NASA Autonomous Rendezvous and Docking (AR&D) CoP is a good example of a focused, grassroots team of engineering specialists from across the Agency that have banded together to not only share and capture their AR&D 'tribal knowledge' but also to plan a strategy for NASA to make the future implementation of AR&D systems effective and affordable to all mission classes. The AR&D CoP is made up of engineering and technology representatives from almost all of the NASA centers and its objective is to provide a forum for technical collaboration in the AR&D arena across the Agency.

Formed in May 2010, the AR&D CoP is a peer-to-peer network made up of NASA technical experts, team leads, and first-line AR&D supervisors. The NESC and the OCE are coordinating the development of the CoP along with representatives of the AR&D communities from across the Agency. The result has been a powerful and influential cross-Agency CoP team capable of more than any single organization.

The CoP recognizes that AR&D is a multi-disciplinary system-level functional capability. While the design and development of space-qualified AR&D systems is typically driven by the GN&C requirements, the work required is not exclusively limited to GN&C engineering. In this regard AR&D is very analogous to

Entry, Descent and Landing (EDL), which is another one of NASA's multi-disciplinary system-level functional capabilities.

The AR&D CoP therefore consists of individuals that are experts in a wide range of engineering sub-disciplines including, but not limited to: systems engineering, systems integration, mission management, sensor design and development, orbital mechanics, modelling and simulation, relative navigation, 6-Degree of Freedom relative control, flight software, fault tolerance/fault management, and mechanical docking systems. This team of experts collectively associated under the aegis of the CoP serves as a one-of-a-kind NASA AR&D think tank which understands the current state of the art, foresees potential issues and problems, and is knowledgeable about future technological needs. In this manner the CoP effectively serves as a technical steward of this important technical capability within the Agency.

The AR&D CoP has the unique overarching ability to identify from within the NASA AR&D 'world' the current technical status of and interrelationship between the AR&D technology/engineering state of the art, existing AR&D related projects, and proposed AR&D future work. This perspective gives valuable insight into the gaps between the state of the art and the desired capabilities for future work as well as the insight to produce relevant new ideas and identify risks to meeting customer needs. All parties benefit from the new ability to feed the CoP observations, findings and recommendations to the Flight Sciences Steering Committee, NESC Review Board, Program/Project leadership, and senior Agency leadership in both the Office of the Chief Engineer and the Office of the Chief Technologist (OCT).

Several techniques and products have been developed to bridge the AR&D CoP team internally and to communicate to the Flight Sciences Steering Committee and Agency leadership. Individual representatives from the various NASA centers have been identified and, together with the CoP Leader (the NASA Technical Fellow for GN&C), they form the core group of this CoP. Communication is accomplished via monthly teleconference meetings and also with an annual Face-to-Face (F2F). These and other communication mechanisms (e.g. a NESC-internal AR&D CoP secure website has been established to post team news and other information) are used to unite the diverse CoP members located across NASA.

In the regular monthly teleconferences, all of which are scheduled and conducted by the CoP Leader, each center representative participates along with other members of the CoP. At these monthly teleconferences the status of current activities are discussed, progress on action items are reviewed, recent community developments are highlighted, and plans for future work

and meetings are formulated. One CoP activity, for example, that is discussed and reviewed at the monthly CoP teleconference is the creation of AR&D technology roadmaps. These roadmaps are a good example of one type of product the CoP generates. This roadmapping is an ongoing activity of the CoP and progress is tracked towards completion of these community-developed technology roadmaps at each monthly meeting.

An AR&D Strategy White Paper has been developed by the CoP as well. This white paper begins with the premise that NASA and the U.S. space industry have yet to develop and demonstrate a 'mainstream' Automated/Autonomous Rendezvous and Docking (AR&D) capability suite. The term 'mainstream' is used here to refer to a capability suite that is considered ready-to-fly, low-risk, reliable, versatile, scalable, cost-effective, and architecture and destination independent. Such an AR&D system could then be confidently utilized operationally on human spaceflight and robotic vehicles over a variety of design reference missions, especially beyond Low Earth Orbit (LEO). In spite of a significant track record of successful rendezvous and docking missions to the ISS involving varying degrees of AR&D capability and other successful demonstration missions of limited AR&D capability, a U.S. mainstream AR&D technology base for a wide spectrum of missions does not currently exist. This is primarily due to the fact that full autonomy and automation has not been required for rendezvous and docking missions as yet. Instead, missions implement varying degrees of autonomy and automation that are tailored for their purposes. Thus, new missions requiring AR&D capabilities continue to incur significant non-recurring engineering (NRE) and development costs related to AR&D component sensors and integrated systems. To ensure mission success and crew safety, and to eliminate costs of continually reinventing the wheel, it is imperative that NASA adopt a strategy which coordinates and integrates all current and proposed AR&D technology development activities into a cohesive cross-Agency strategy to produce a mainstream U.S. capability. If this goal can be accomplished future missions would benefit from significant risk reductions in technical performance as time progresses. The NASA AR&D community believes this is a highly desired outcome, which is achievable in the next five to ten years. A strong commitment by Agency leadership to a strategic direction based on an evolutionary, stair-step development, through a campaign of coordinated ground tests and space-based system demonstrations of AR&D component technologies will yield a multiple-use mainstream AR&D capability suite.

Other examples of CoP products include online, easily accessible and searchable, databases of AR&D sensors, algorithms, and test facilities. These databases

have been developed for the use of the CoP members and also as a handy resource for all NASA engineers and scientists.

As previously mentioned, a face-to-face (F2F) meeting of the CoP is also held on an annual basis. The venue for this F2F meeting changes each year but typically it is held at a NASA center. In this F2F forum the members of the CoP work together to step back and review past accomplishments, share the latest community information, and most importantly, strategize and formulate plans for the next year's activities. For example, it was at the 2010 CoP F2F, held at NASA's Jet Propulsion Laboratory (JPL) that the concept of performing a low-cost in-space technology demonstration of the Vision Navigation Sensor (VNS) was initially conceived of by the CoP members. The VNS technology demonstration activity, formulated and initiated by the AR&D CoP, and co-sponsored by the NESC, has been a positive much-needed activity in the AR&D arena. The VNS is a laser-based flash LIDAR sensor that determines range and bearing to optical reflectors mounted on a target vehicle. Under NASA's Constellation Program the VNS was originally baselined as the primary rendezvous, proximity operations, and docking sensor for the Orion crewed spacecraft.

The VNS idea developed by the AR&D CoP ultimately intends to exploit the ISS as an on-orbit GN&C technology validation laboratory. The CoP realized the lack of critically-needed in-space relative navigation sensor technology demonstrations and as a group brainstormed and refined the idea for a near term relatively low-cost alternative. The CoP identified the need to mature GN&C relative navigation sensor component technology. Existing VNS engineering development unit (EDU) hardware, was obtained by the NESC from the Orion Project and is currently in the process of being assembled, calibrated, and tested by the sensor vendor. Once assembled and tested the VNS EDU, depicted in Fig. 5, will become an asset for the AR&D CoP. It will first be delivered to GSFC for integration into an AR&D ground testbed. In parallel with the VNS EDU ground testing activity, plans are currently being formulated by the AR&D CoP to fly this unit to the International Space Station (ISS). The envisioned VNS EDU flight experiment on ISS will significantly mitigate the technical risk of using this type of flash LIDAR relative navigation sensor technology on-board the Orion crewed spacecraft and a number of other future NASA spaceflight applications, including the Mars Sample Return mission. Flying the VNS EDU on ISS will allow for the testing and validation of relative navigation and vehicle pose estimation algorithms in a realistic operational environment over a broad range of dynamic and lighting conditions.



Fig. 5: VNS Engineering Development Unit (EDU).

The AR&D CoP is important to NASA's future in several ways. The CoP members are working to communicate to both their colleagues and to senior NASA decision makers that the ability of space assets to rendezvous and dock is a critical enabler for both human and large-scale science exploration, as well as satellite servicing/rescue, and is therefore an essential functional capability for the future of NASA. The AR&D CoP performs a unifying role that was previously missing within NASA. Prior to the formation of the CoP, individual AR&D engineers, technologists, and managers worked in a stovepiped manner at their individual NASA centers. The CoP provides an excellent but informal environment for technical exchanges and collaboration across the Agency. The CoP has voluntarily brought together engineers from across NASA that previously might only have had brief technical interactions and 'hallway' encounters at conferences or symposiums. The framework and operations of the CoP allow for and encourage the building of not only an AR&D technical communications network, but more importantly the establishment of permanent trusting relationships between the members from the various NASA centers. That was not always so easy to accomplish prior to the formation of the CoP since direct contact was limited and often encumbered by differences in the center engineering cultures. Quite possibly it is these trusting relationships that will be the most enduring and potentially high-payoff products of the CoP.

A very good example of where these relationships paid off was in response to the recent Office of Chief Technologist Broad Area Announcement (BAA) that solicited proposals for Technology Demonstration Missions for rendezvous and proximity operations technologies. The established CoP working relationships nurtured a productive environment in which the members could discuss potential proposal topics, approach other members to become teammates and ultimately to collaborate on synergistic joint proposals for submittal to the OCT.

### The Fault Management Community

In this paper we have already discussed how the formation and use of the CoPs can help NASA both capture undocumented engineering ‘tribal knowledge’ before it walks out the door and to overcome the inhibiting effects of insular professional development in rigidly stovepiped organizations. Now we consider the benefits of creating a CoP with the specific objective of supporting the development and coalescing of a new and emerging engineering activity or sub-discipline that is still in the formative stage. In this particular case we are talking about the sub-discipline of Fault Management (FM) at NASA. FM is a non-traditional (relative to say the Structures discipline) engineering activity most often affiliated with the Systems Engineering discipline or in many other cases the Software Engineering discipline. Generically speaking FM encompasses functions that enable an operational system to prevent, detect, isolate, diagnose, and respond to anomalous and failed conditions interfering with intended operations. FM focuses on the off-nominal behavior of a system and it is a subsystem in its own right found on most NASA spacecraft. Similar to GN&C, Avionics, Structures, etc., FM is a subsystem which must be architected, designed, developed, integrated, tested and operated by NASA engineers, scientists and technicians. From a methodological perspective, FM includes processes to analyze, specify, design, verify, and validate these functions. From a technological perspective, FM includes the hardware and control elements, often embodied in sensors, software and procedures, of an operational system by which the capability is realized to autonomously respond to faults, anomalous conditions, and hazards. For example, a robust onboard FM system, tightly integrated with an autonomous GN&C system, is envisioned to be key element of any future NASA space platform operating beyond Low Earth Orbit (LEO).

Clearly FM engineering is an important part of the complex worlds of both human and robotic spaceflight at NASA but it is not easy to define, understand or effectively practice. Because FM is still in the formative stage, the engineering leadership at NASA decided to form a CoP focused on this emerging sub-discipline. Some of the primary objectives of this new CoP are the following:

- Provide an easy to use online forum for technical interaction and knowledge sharing between practitioners and managers across the FM community at NASA
- Define, establish, and obtain a NASA-wide community consensus on a common set of FM nomenclature
- Identify, document, and compare the different approaches for FM used across NASA, at its

industry partners, and other organizations such as DoD.

- Identify, capture, and disseminate FM lessons learned from past NASA programs and projects
- Provide a set of relevant probing questions to be posed at the specific FM system developmental milestones
- Educate and inform space system architects and program/project stakeholders on FM, making them more aware and conversant in the issues and design options early in the development cycle
- Identify, develop, and host tools/methods to properly scale (‘right-size’) FM systems relative to cost and risk
- Identify, develop, and host analytical methods and techniques to help FM system designers balance/optimize automation versus human-in-the-loop (both in space and on the ground)
- Foster better communication and understanding of the challenges, options, and technologies of FM as applied to long duration spaceflight, especially with crewed vehicles

A system-level perspective is required for FM, as it is not merely a localized concern. A system’s design is not complete until potential failures are addressed, and comprehensive FM relies on the cooperative design and operation of separately deployed system elements (e.g., in the space systems domain: flight, ground, and operations deployments) to achieve overall reliability, availability, and safety objectives. The goal of FM is the preservation of system assets, including crew, and of intended system functionality (via design or active control) in the presence of predicted or existing failures. Like all other system elements, FM is constrained by programmatic and operational resources. Thus, FM practitioners are challenged to identify, evaluate, and balance risks to these objectives against the cost of designing, developing, validating, deploying, and operating additional FM functionality.

The FM CoP recognized early on that although fault management is a maturing discipline, there currently is no unifying description or set of guidelines for this field. The current situation begs the question “Why is it acceptable to have a collection of *ad hoc*, uncoordinated approaches for FM, when it is not acceptable for any other safety-critical design process?” “This is what we have always done” is an insufficient answer, especially in the presence of program cost overruns, schedule slips, and in-flight failures traceable to a lack of disciplined approaches and systematic methods.

The CoP members understood that since FM is a key factor to increase safety, reliability, availability, and performance in systems, it should have the rigor of other safety-critical processes in order for significant

improvements to be made. If the field does not mature by developing, documenting, and applying systematic methodologies for developing FM functionality, improvements to safety and reliability will be limited.

It is for all the above reasons and motivations that the FM CoP undertook the task of developing, for the first time, a NASA FM Handbook as a necessary step toward maturing the field. This handbook is the first tangible product to be delivered by the CoP. [14] FM is overdue to move from an 'art' to a 'science,' characterized by a known, agreed upon, and consistent methodology to structure FM and its relationship to other branches of engineering and design. The insights and concepts captured in this handbook provide a basis for moving the field toward a formal and consistent FM methodology to be applied on future programs.

#### V. CONCLUSION

The communities of practice on NEN have already proven their worth to the Agency. At first they were focused on collecting information such as specifications, contact lists, and training opportunities. This alone was a breakthrough for the Agency; to be able to find key resources in one location was a major step forward. As more people began to use the communities, they evolved into more interactive sites where engineers suggested content, found peers to help with pressing problems, and benefited from knowledge-sharing presentations. Key documented information has been captured and engineers have been able to network with their peers and work together to improve NASA's engineering disciplines. Practitioners have been given access to a cadre of ready experts available to answer their questions. Communities have been formed to apply focused attention on important niche technical areas, such as AR&D technology and engineering. These communities identify and capture undocumented engineering 'tribal knowledge' and serve to counteract the constraints on professional development found inside insular engineering organizations. Alternatively, some communities, such as the FM CoP, have been established with the specific objective in mind of fostering the development and coalescing of new and emerging engineering activities still in the formative stage. All these communities are still in the early stages of their growth. As they continue growing and become more prevalent at all the centers, they will become even more valuable to NASA.

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NEN can be accessed by NASA personnel at <https://nen.nasa.gov>.

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