



Journal of Aerospace Technology and  
Management

ISSN: 1948-9648

secretary@jatm.com.br

Instituto de Aeronáutica e Espaço  
Brasil

Bergue Alves, Miriam C.; Morais, Ana Marlene F.

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Journal of Aerospace Technology and Management, vol. 1, núm. 2, julio-diciembre, 2009, pp. 265-272

Instituto de Aeronáutica e Espaço

São Paulo, Brasil

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Miriam C. Bergue Alves\*  
Institute of Aeronautics and Space  
São José dos Campos- Brazil  
miriamalves@iae.cta.br

Ana Marlene F. Morais  
Institute of Aeronautics and Space  
São José dos Campos- Brazil  
ana.morais@iae.cta.br

\* author for correspondence

# The management of knowledge and technologies in a space program

**Abstract:** This paper presents an ongoing work at the Institute of Aeronautics and Space (IAE) to provide a process and a system to support the management of knowledge and new technologies applied to the conception and development of the Brazilian Satellite Launcher Program. This management is not only necessary to organize the actual research efforts but also to identify communalities and necessities for the strategic planning of future research projects and development activities. The results of the research projects are usually new technologies that ought to be employed in the development of the Launcher Program. The proposed knowledge management system will not only enable assessing these new technologies but also help in defining and planning the research topics in each important area of this multidisciplinary program, according to the Institute's strategic goals and space mission.

**Keywords:** Space systems, Technology, Knowledge management, Research projects, System engineering.

## INTRODUCTION

In general, space programs deal with complex systems that apply high technology as well as investigate solutions for new and singular problems that arise in the space realm. This is one of the reasons for the high dependency level on government and commercial stakeholders for space capabilities.

The mix of technical professionals from industry, academia, and government is widespread in these programs. This combination of expertise has to be well coordinated in order to have a well balanced investment in basic and applied research, resulting in the necessary technologies for the success of a space mission.

Another considerable concern is the strategic aspect of such technology. Nowadays, the partnership with other similar international institutions and academia is crucial for the sustainability of such programs and also for cost reductions. However, considering the growth in the commercial use of space technology, these partnerships have to be based on solid agreements between the governments in order to preserve their own interests.

Complex space systems also require serious systems engineering with careful planning and attention to the process. The management of knowledge and technology in these programs is becoming even more important as the complexity increases. The launching environment, for instance, is unique and the launching event lasts only

minutes, however it requires a great deal of integration of the effort and resources of the systems engineering.

Considering all the challenges ahead, the research and development process of new space technologies ought to be a well-controlled one, with clear goals defined, a timetable set up and a range of costs established. The human resources and risks also have to be managed appropriately. Given that resources are not unlimited, controlling this process is a “must” for the success of any space program.

This paper presents an ongoing work developed at IAE to provide a process and a knowledge management system to deal with new technologies applied in the conception and development of the Brazilian Satellite Launcher Program. The knowledge management is necessary not only for organizing the actual research efforts but also for identifying communalities and necessities for strategic planning of future research projects and development activities.

The next section presents the peculiarities of system engineering in a space program, followed by the section where the methodology is presented. Then some results are discussed, followed by the final conclusions.

## THE COMPLEXITY OF SPACE SYSTEMS ENGINEERING

Systems engineering plays a fundamental role in projects that involve emerging technologies and can

Received: 23/09/09

Accepted: 29/10/09

be defined as management technology (Sage, 1992). Organization, projects, and production of scientific knowledge are intrinsically associated with the systems engineering life-cycle and, although space systems follow the same fundamental systems engineering principles as any other system, there are particularly challenging aspects of space systems that need special consideration.

Space systems engineering involves the challenges of a rigorous launching environment, where the structural elements of both launcher and satellite must be designed to resist the remarkable forces due to the thrust of the launcher motors and vibrational and acoustical forces. Sensitive electronics and sensor elements must also resist the shock conveyed by pyrotechnic devices used for the launcher's stages separation and the deployment of a satellite. There are also tight constraints on both mass and volume that impact in costs.

Costs play an important role in these programs (Wertz and Larsen, 1996). The greater the lift capability is, the more expensive the launcher will be due to the orbit the mission wants to reach. The design of big structural elements demands new technologies and original concepts has to be developed.

All the elements and issues mentioned before have to be brought to a system engineering life-cycle, whereas a number of activities, grouped in phases, should be realized in an interactive and iterative way, with the purpose of delivering a product or system that fulfill the space mission requirements. In the case of space systems, a big part of the requirements are transformed in technical and functional requirements that typically demand new knowledge, therefore implying in research efforts.

Other mission requirements are converted in system management requirements that will guarantee the development of a product or the delivery of a service. Additionally, in a large and complex space system there is another management component, called knowledge management.

Technological projects, unlike most others, have the potential to fail to meet their goals. If it is a new technology, the implied risks are higher.

The areas of research involved in the Launcher Program encompass structural dynamics, control, thermal, space power, propulsion, and software development. Such multi-disciplined approach demands the best use of knowledge to achieve organizational objectives.

## Innovation

Innovation means ideas applied successfully, differing for invention that is an idea made visible (McKeown, 2008). Innovation generates technology and it results from research and experimentation, which implies that the organization has to clearly define its goals, and based on these goals establish and conduct the necessary research in a controlled way.

There is a myriad of possible ways to seek for solutions and produce advanced technologies in the context of a multidisciplinary and complex space program, so the conduction of research has to be carefully planned. In order to prioritize specific knowledge areas for investment, at least the following aspects should be considered:

- A thorough benchmarking of what is already available in the space market;
- The associated costs;
- Acquisition crisis;
- Unanticipated failure modes of the Program;
- Development problems with individual elements that can cripple the schedule and budget;
- Uncertain technological changes.

Based on an analysis of these aspects, a plan has to be elaborated, including strategic goals and directives for the space program. This plan is crucial for kicking off a knowledge management process and organizing the research efforts.

Once the goals are established, it is extremely necessary for the organization to come up with a process to deal with the on-going projects portfolio and all the technologies that may be generated, including their results. The process to be adopted at IAE is presented in the "Methodology" Section and it is intended to provide a complete view of the Institute in terms of the main topics of research, projects and results, applied technologies, human resources involved in research, and related costs.

Most of the solutions for space systems problems depend on new knowledge, which has to be provided by new technology. The research is necessary to support the effective application of technology in support of the space program's needs. Scientific research advances the frontiers of knowledge, and technically there is no final point.

It is highly desirable that the performance of the space systems is improved as an outcome of research, but the definition of the mission's success has to be clear in order to avoid that these systems continuously remain under development.

The establishment of an efficient system to deal with innovation at IAE should be based on concrete information about the relationship between the main research areas and the Launcher Program's strategic goals. The research groups are composed by research topics, which have related research projects. The research projects are the main course of action to generate technology applied to the Launcher development.

Once this information is available and updated, actions may be taken in order to organize the research initiatives in a few and principal research groups that are aligned with the Institute's strategic goals. In this manner, these groups will grow stronger with the organization's support.

The core idea behind the advanced research projects at IAE is to pour over the necessary investments when conducting a space engineering project. Therefore, the results of these projects will be converted into requirements and technology applied to the Launcher Program. Consequently, a technology transfer plan may be elaborated to pass on the project's findings to the development team, which works within the mission's restrictions.

This knowledge transfer is fundamental to define a space system baseline for the designers to advance in the design and construction of the system, measuring time, sizes, and development costs.

As a collection of new technologies in their early development stages is produced, as a result of advanced research projects, it is essential to incorporate these emerging technologies in the Launcher development, envisioning a real mission.

However, incorporating emerging technologies into a real mission is not as simple as it appears to be. It is necessary to employ the adequate system engineering technique to enable the transition and insertion of these technologies into current and future space systems. This process does not start when the research project is concluded, but rather back to the initial research project proposal, when it should be established what results are expected and how the generated technology will enhance certain capabilities and/or provide new functionality for the space system. This information will be crucial when judging the research project proposal and its approval by the Institute, as established in the next section.

Since research projects are related to a diversity of areas, it was essential for IAE to set up an effective knowledge management system to keep total control of what has already been done, what is necessary, the health of the research projects, and the effective connection of these projects to the Launcher Program.

## **METHODOLOGY**

### **The process of knowledge exploration**

The process of knowledge exploration is aimed at fulfilling the established needs of new technologies to solve problems inherent to complex requirements of the space system. It is an organizational process for converting information into knowledge and making that knowledge accessible.

Complex space problems have to be broken down into smaller, more manageable pieces. These pieces are converted into subsystems that are undertaken with a multidisciplinary approach. In the case of IAE, there are five fundamental factors that are considered during the process of knowledge management and exploration in order to reach the desirable effectiveness and efficiency.

The first factor considered is the knowledge transfer factor. Its effectiveness will be achieved only when there is an efficient process, incentive, or reward for delivering a particular required technology.

The second factor is the research project's relevance factor. At IAE, research projects are the means to advance in several research areas, hence generating technology. A multidisciplinary approach is employed to assess and approve new project proposals, based on their best use of knowledge and their alignment with systems engineering, avoiding to approve projects that bring up solutions for problems that were not even defined. There are specific criteria for project approvals and it involves the collective interest of stakeholders and the organization strategic objectives.

The human resource factor is very strategic in this context, and is the most valued asset of an organization (Armstrong, 2006) - the working team contributes individually and collectively to the achievement of the objectives of the primary mission. The knowledge and experiences acquired by the teams in former research projects, activities, and lessons learned are taken into account when deciding which research project proposal to approve.

The fourth factor is cost and time factor. This factor is important to assess the costs related to the research development, considering the time such new technology will take to become mature enough to be employed in a space project. This factor has a direct impact in the research projects assessment, bringing to light the necessary investment in new infrastructure, the reuse of the current installations, the need for new acquisitions and the project planning and schedule.

The last factor, risk factor, is intrinsically connected with costs and the system's performance. The research project has to satisfy the needs and a set of specifications in a manner that it is cost effective and it conforms to a predetermined schedule with an acceptable risk, keeping a satisfactory performance. The inherent risk estimation should also consider the technology's readiness level (DOD, 2001).

Figure 1 illustrates these five factors in a context of knowledge management exploration at IAE.

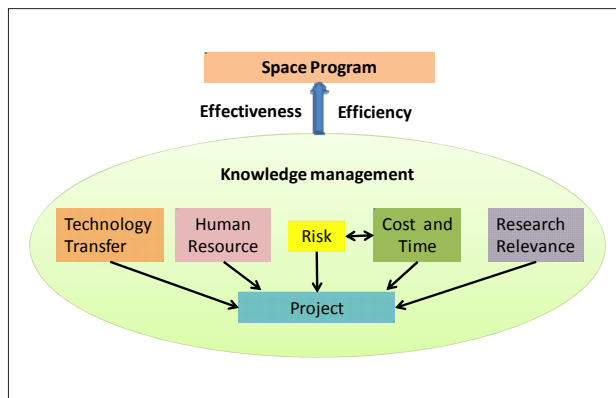


Figure 1: The 5-factors and the knowledge management context.

If all these factors are considered in the process of knowledge management exploration, and, if this relationship is well coordinated, it will bring effectiveness and efficiency for the space program.

One of the crucial points of knowledge management in a space program is to recognize the differences between the real space system and research projects and, consequently, implement scale-appropriate strategies to technology transfer.

Research projects are usually small in size and require small teams to carry out all the work while a real space system requires established subsystem responsibilities, team discipline, and the ability to manage and react to changes. These established differences imply that different methods are necessary to meet the needs of both; research projects and space systems. In order to improve the probability of the mission success, there are system engineering techniques that exclusively apply to space systems.

NASA makes implementation decisions and defines what is acceptable for a mission based on a traceability matrix (NASA, 2008) that captures the connection between the scientific objectives, the scientific measurement requirements, the functional requirements, the preliminary implementation strategy, and the preliminary performance of the proposed system.

## Research Projects

Research projects, as aforementioned, are the means to explore the scientific goals of the IAE Launcher Program and, as a result, to transition the resulting applicable technology into practice.

The selection of new research projects must make full use of the existing knowledge by correlating separate sources and showing how they can effectively be exploited.

The research teams have to work toward a common goal, without duplicating efforts, conflicting subsystems design, or incompatible interfaces. These interfaces have to be well defined and controlled.

Another point to consider when establishing new research projects is the analysis of the critical success factors of the space mission in which good results will increase the necessary performance for its completion. This analysis will help reducing the principal investigators insistence on conducting state-of-the-art, complex and risky research projects (Bitten, Bearden, and Emmons 2005). Performance requirements that are based on chief technologies should consider their maturity (Mankins, 1995).

At IAE, the main investigators and their teams are organized in main research groups (RG) related to a space program knowledge area. These RGs usually have more than one main research topic (RT). The research projects (RP) are often connected to one or more RTs.

In order to manage future research projects and resulting technologies, a knowledge management system containing all the possible information on RGs, RTs and RGs was essential, not only to make the right decisions about the research strategic investment, but also to evaluate research project proposals.

With a decision support system based on knowledge management, much of the information available in the research proposal can be checked for consistency and reasonableness, in order to avoid, for example, the overloading of human resources and duplication of infrastructure.

A Committee comprised of two investigators from each main research area of the Launcher Program, is responsible for assessing the project proposals that are submitted.

The Committee determines whether these proposals will or not become selected research projects based on a final grade given by the Committee members. The project evaluation and final grade is based on the fulfillment of the evaluation criteria established in Table 1, which can be quantified and classified in 5 levels, as shown in Table 2.



Table 1: Evaluation Criteria.

<b>Research Projects Evaluation Criteria</b>	
1.	Association with the the Institute's high-priority strategic objectives
2.	Relevance of the project proposal in the space systems research context
3.	Relation with the main research areas established in call for submission of RP
4.	Relevance and justification to conduct the RP
5.	Relationship between the RP and the Institute's knowledge base
6.	Clarity of the project goals and expected results
7.	Identification of the measures of the project success
8.	Innovation of the research products
9.	Scientific methodology (logical and coherent description to reach the final research goal)
10.	Qualification of the research team
11.	Reasonableness of cost and schedule
12.	Needed infrastructure for the project development
13.	Proposed infrastructure useful across multiple RP and RG's
14.	Direct applicability of the RP products to the target domain and across multiple projects and RG upon completion.
15.	Usefulness of products
16.	Technology Transfer Plan
17.	Development of human resources
18.	Identification of the environmental risks, if it is the case, and the procedures for minimizing them
19.	Overall quality

Table 2: Evaluation Criteria Fulfillment.

<b>Grade</b>	<b>Classification</b>
5	Complete
4	Good
3	Regular
2	Minimum
1	None

A list of selected projects is elaborated in which a priority is established for each selected project based on their final grade. The Brazilian Space Agency (AEB) provides the research grants for the selected projects based on this list.

During the research project development, a constant project monitoring is performed by tracking its main milestones and resulting products. The assessment of the projects' generated technologies can be done in different ways, and it is usually quite challenging. One of NASA's successful technology transfer measurement can be exemplified in one of their key measures of project success called Penetration Factor (McGill et al., 2006).

Once the research projects are approved, the Research & Development Coordinator (R&DC) is responsible for keeping track of each project's status. There is a very simple computer system, called Project Tracking System, used for the communication between the R&DC and the projects' manager, enabling the latter to register actions taken and to upload new deliverable releases of the project. This system can provide up-to-date projects data to the proposed knowledge management system.

The final assessment of the project results considers the space program's goals and the requirements to produce a well-defined and useful set of measures to analyze the research project's efficiency and efficacy. The measures of the project's success will consist of a set of quantitative and qualitative information including the following data:

- Technology delivered;
- Projects' outcomes that generates successful technology transfer for the space program;
- Appropriate combination of basic and applied research, if it is the case;
- Descriptions of lessons learned;
- Research accuracy in meeting the original selection criteria to include technology transfer potential;
- Interaction with other RGs;
- Uncertainty of the results and conclusions.
- Waiver of the results compared to the initial project goals and theories;
- Experiments with inconclusive or negative results;
- Procedures that can guarantee the data exposition and tests reproduction;
- Generalization of the results for more general cases.

The evaluation of the resulting technology of a research project will also consider the technology readiness level (TRL). Therefore, categories of technology readiness levels from DOD 500.2R (Department of Defense, 2001) will be used for identifying the maturity of the technology. The resulting technology has to be at least level four in order to be employed by the Space

Systems Engineering. All of the project information will be collected and then inserted into the knowledge management system, which will also have information concerning Research Groups, Research Topics, and Research Projects. Since all of this information will be connected, it can be used to define new strategies and managing correlated technology.

### A process to define strategies

The Institute's main research areas of interest have to be constantly reviewed to reflect technology readiness, projects results, lessons learned and, most importantly, the Institute's goals. These goals will drive the definition of strategies for future works and justify the investments and research in new technologies.

Once the main research areas are reviewed, the flow of technology from research to actual practice and its employment in the space program is achieved by carrying out research that is externally valid as well as accepted in the national and international space community.

Figure 2 presents a pictorial view of the proposed process that is being implemented in the Institute. This process is strongly based on the knowledge management system that was described as a sustention pillar to manage the correlated technologies within the Space Program.

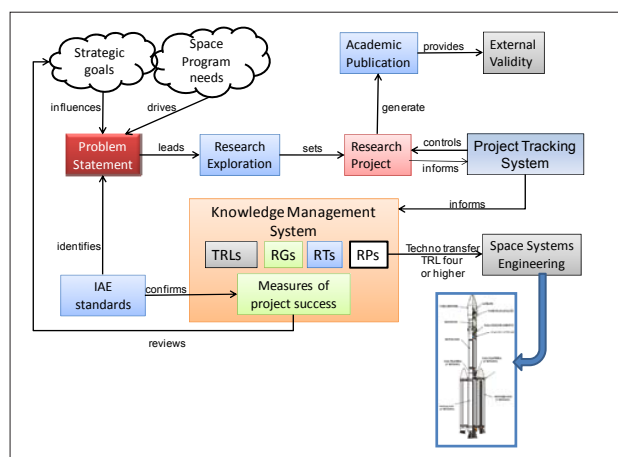


Figure 2: The proposed process for managing technologies.

As Figure 2 depicts, the process may be started by a problem statement, based on Space Program needs, on the Institute's strategic goals or identified by an IAE need for standardization. Establishing a problem can start a new research that determines the research projects. Once the research projects are approved, the Project Tracking System starts tracking these projects

regarding schedule, costs and achievements. The projects may also generate academic publications that will be evaluated by an external community. The Project Tracking System sends research project information to the Knowledge Management System, hence providing useful information to the system engineering and decision makers, according to IAE standards and strategic goals.

Another powerful drive of the process shown in Figure 2 is the collaboration amongst the investigators. The researchers should collaborate with each other in the Institute in order to identify communalities and maximize the expertise. Collaboration amongst the research groups is highly desirable and motivated by promoting easy access to up-to-date information about research groups and their members, research topics, research projects under development, project results, and the research groups' scientific production.

This information is available in the knowledge management system. In order to have strong research groups, with a well defined structure, they are evaluated using a specific set of criteria also available in the system. The stronger the group, the more chances of obtaining grants for projects research.

The improvement of communication among the researchers, developers, practitioners is a must, which is crucial for the integration of scientific research to system engineering activities.

## RESULTS AND DISCUSSION

The conception and development of a knowledge management system was necessary to provide the right information at the right time to make the right decisions in order to improve the Institute Space Program's effectiveness and efficacy, as illustrated in the Figure 1.

The main idea of this system is to organize and to store information about the RGs, RTs, and RPs, capturing the experiences of investigators and research groups, the resulting technologies and their association with the Space Program. Additionally, the design, review, and implementation of both social and technological processes help to improve the application of knowledge in the Institute.

Figure 3 illustrates the schematic idea adopted in the conception of the knowledge management system. This Figure shows the important role of the research projects as generators of new technologies. The adequacy of the research project for the Space Program's goals is given by its measures of success.

Figure 3 also illustrates the hierarchy between projects, research topics, and groups, reinforcing the power of projects in this context.

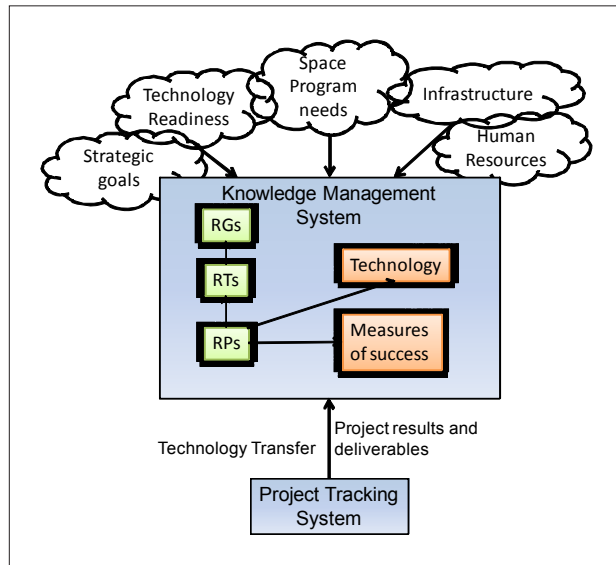


Figure 3: A schematic idea of the knowledge management system.

A database to implement the knowledge management system is now under development. It stores all the data related to the RGs, RTs, RPs, HRs and their relationship. The sets of criteria used to evaluate project proposals and research groups are also incorporated in the system, as well as the TRLs. The database was designed to keep up with the dynamic aspect of a knowledge management environment.

A user friendly interface was designed, providing an extensive set of possible queries by all of the staff at the Institute. The insertion of new information and its updating is easily done by authorized personnel and is certified by the R&DC.

The knowledge management system access is done via a web based browser, available in the Institute Intranet. All the system information can be extracted and visualized anytime by all the investigators and members of the organization, using the existing query mechanisms.

## CONCLUSION

This paper presented an ongoing work at IAE to promote the best use of the available knowledge to manage the correlated technologies and employ them efficiently in the Brazilian Satellite Launcher Program. A process was defined to carry on these activities and a knowledge management system is under construction to support it. The knowledge management is based on the fact

that research projects are potential generators of new technologies for the Program. The multidisciplinary aspect of the Program results in research projects linked to specific research topics. These research topics are aggregated to the research groups.

One of the expected benefits with the implementation of the proposed process and the core knowledge management system is the assurance that the intellectual capabilities of the Institute are shared, preserved, and institutionalized.

The justification of the investments in research is another side of the coin. The Brazilian Space Agency will carefully look at past research projects and the effective application of their results to the Launch Program in order to concede grants for future research projects. This fact increases the responsibility of the Institute in promoting strategic research that adequately fits its space mission.

Suggestions from researchers to make improvements in the space program will be stimulated as well as the involvement of practitioners and developers in research design needs. This initiative will improve the research projects' evaluation and selection and also grant them recognition.

Improvements will certainly be necessary in the process and in the original system conception to incorporate new requirements as the process increasingly matures, integrating more sophisticated techniques for data visualization, graphics, animation, 3-D displays, and data mining.

The final aspiration of this work is that the overall benefits of a knowledge management will be found in tomorrow's new space programs.

## ACKNOWLEDGEMENTS

This work was partially supported by the Brazilian Space Agency –AEB.

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