ASTRIC - Design and control of cooperative robots for rapid deployment in asteroid impact deterrence missions

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The problem of trajectory deterrence for asteroids detected with short notice before high-probability of impact with Earth demands the ability to select from a number of manipulative operations in a real-time operating environment that may not allow for constant or reliable human-machine communications, and which may require significant cooperativity among multiple robot devices in deep space. ASTRIC is an engineering program designed to produce an integrated system for such challenging remote space-based robotic missions. Its emphasis is upon adaptive intelligent multi-agent control of modular, reconfigurable, fault-tolerant components operating as semi-autonomous networks. We describe here the foundations of the core components of the architecture and the methodological approach for a cybernetic engine capable of controlling high-velocity objects operating with low tolerance for error in settings where uncertainty and noise are both likely to be high due to distance and limited target observability.

I. Introduction

ASTRIC has its roots in "legacy" projects conceived over 20 years ago including seminal efforts to establish a permanent orbital platform for planetary environmental remote sensing [1]. Presently it is a consortium program underway involving researchers in several countries including Russia, Finland, Spain, Germany, Korea and USA. "ASTRIC" = "Astro-Terrestrial Robotic Interaction and Construction" and this is a significant departure from the original "space-centric" focus of the work. Emphasis is upon control systems and the exceptional need for asteroid-related missions (not only for impact deterrence through trajectory modification but for future practical mining, manufacturing, and other industrial applications) to incorporate more robust control systems that can accommodate radical and non-linear state-space changes within the overall system and that can handle the non-deterministic, non-computable (in real time; i.e., "NP-hard") problems that are likely to arise during such a mission in deep space or even distant earth orbit.

ASTRIC is also placing emphasis upon the unique similarities, rather than only the differences, between multi-agent cooperative semi-autonomous devices operating in Earth's gravity and within air or water, or on land, and those operating in the seemingly very different environments of asteroids, moving freely within interplanetary space, with sizes from @ 20m to more than 1 km in average dimension and only micro-fractional gravitational fields compared to that of Earth. Foremost in this regard, the ASTRIC team has determined that several earth-based robotic and control environments lend themselves very well as models and prototypes for an ASTRIC mission. The objective is to perform not only computer-based simulation and modeling but also physical experimentation, "on the ground," so to speak, using UAV, UGV and AUV apparatus, in cooperative, competitive, and "coopertition" (a

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hybrid of working together and competitively) conditions, and in this way achieve greater engineering accuracy and optimality – and with fewer negative surprises – once the ASTRIC system can be deployed in remote space.

Of the earth-based applications that have been analyzed and studied in comparison with the type of asteroid missions ASTRIC will perform, two such types have surfaced as optimal for both technical and practical project reasons, for inclusion in the modeling, design and experiment phases of work - mine safety and agriculture. The basis for this choice is twofold and will be explained further within this paper:

(1) Certain mechanical and especially multi-unit, multi-surface tasks are such for both navigation, sensing, monitoring and constructive/destructive operations within mines, and within certain agricultural environments such as orchards and vineyards, that test-case experiments can be performed in these environments that will enable testing and refinement of comparable devices that will need to operate with asteroids of varying geometry and composition.
(2) From the standpoint of practical program management and sponsorship, the fields of terrestrial mining and agriculture are high-need, high-demand areas for research and practical application development in robotics and also excellent opportunities for engagement of partners within industry and within the educational community. This affords the ASTRIC program an advantageous and strong “hand” in the challenging world of support, funding and sustained sponsorship. A project like ASTRIC demands sustainability over years, not months. A first mission launch, contemplated to converge with the proposed and recently announced “Deep Space Gateway” (DSG) manned lunar station (US + RU), requires consistent and unified efforts by a diverse team of specialists and coordinators. Such a team has been identified and assembled, and is in the process of conducting its work. It is essential to maintain the momentum and to maximize energies to the task of designing innovative modular and “soft”-limbed robots, and giving them the adaptive synthetic intelligence (ASI) that will enable both human-control and machine-driven self-control, in an operational situation that may be minutes away for one-way light-speed communication.

Certain tasks to deflect an asteroid’s trajectory and convert a “certain impact” into a “definite by-pass” may allow for time to conduct several contact approaches and several operations, even with different technologies (e.g., netting and tethering, laser, ballistics, kinetics, gravitational mass, or in an extreme case, a nuclear detonation). Others, however, for which ASTRIC must be adequately and sufficiently designed – and thus the strong emphasis upon control and the cybernetic intelligence onboard and within – will allow for only one chance. And that may be a critical “one chance” affecting all living on planet Earth.

Figure 1 provides an illustration of those known and detected small asteroids, (1 – 20m in approximate diameter) that reached Earth’s atmosphere. There are several thousand high-impact asteroids that are known and tracked, and an indeterminate number of others that are unknown in terms of size, trajectory and impact potential. Of those that have at least come into the atmosphere, in recent historical times, the Tunguska Event of 1906, in eastern Siberia, stands out as memorable due to its vast devastation of the Siberian forest (destruction of over 80M trees spanning @ 2,150 m^2). However, fortunately, at that time, there were no known settlements, even small towns, in that region. Today, millions live in that general region, and there are few places on the planet’s continents that would be remote and untouched in a Tunguska-type impact. That asteroid is estimated at having been not much more than 50m diameter. Its explosive impact is estimated at being 10-30 megatons.

The 2013 Chelyabinsk Event, however, was a different story. By great fortune, the 17-20m diameter object exploded approx. 30 km above the earth's surface and the blast effect, estimated at 400-500 kiloton, was comparatively minimal to what it could have been at a much lower altitude. Nonetheless, over 1,040 people were injured and over 7,200 buildings damaged, in an elliptical area of around 100km width and 30-40 km in length.

While a comprehensive and complete planetary advance warning and defense system is not realistic, what is possible is a countermeasure system that can work with data from the several NEO (near earth object) detection systems currently operational or planned for future deployment. Such systems include several developed and managed by NASA (Scout, Sentry, Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)), and others including ATLAS (University of Hawaii), Sentinel, AstroidFinder and several analytical programs from ESA (EU), JAXA (Japan), NEOShield (European consortium). As the capabilities for detection and advance warning increase in sensitivity, span, distance, and accuracy, the opportunity and demand for a robust response system grows, and efforts led by ESA, NASA and JAXA have been under development and now deployment, including OSIRIS-REx, DART, ARM, and Hayabusa.

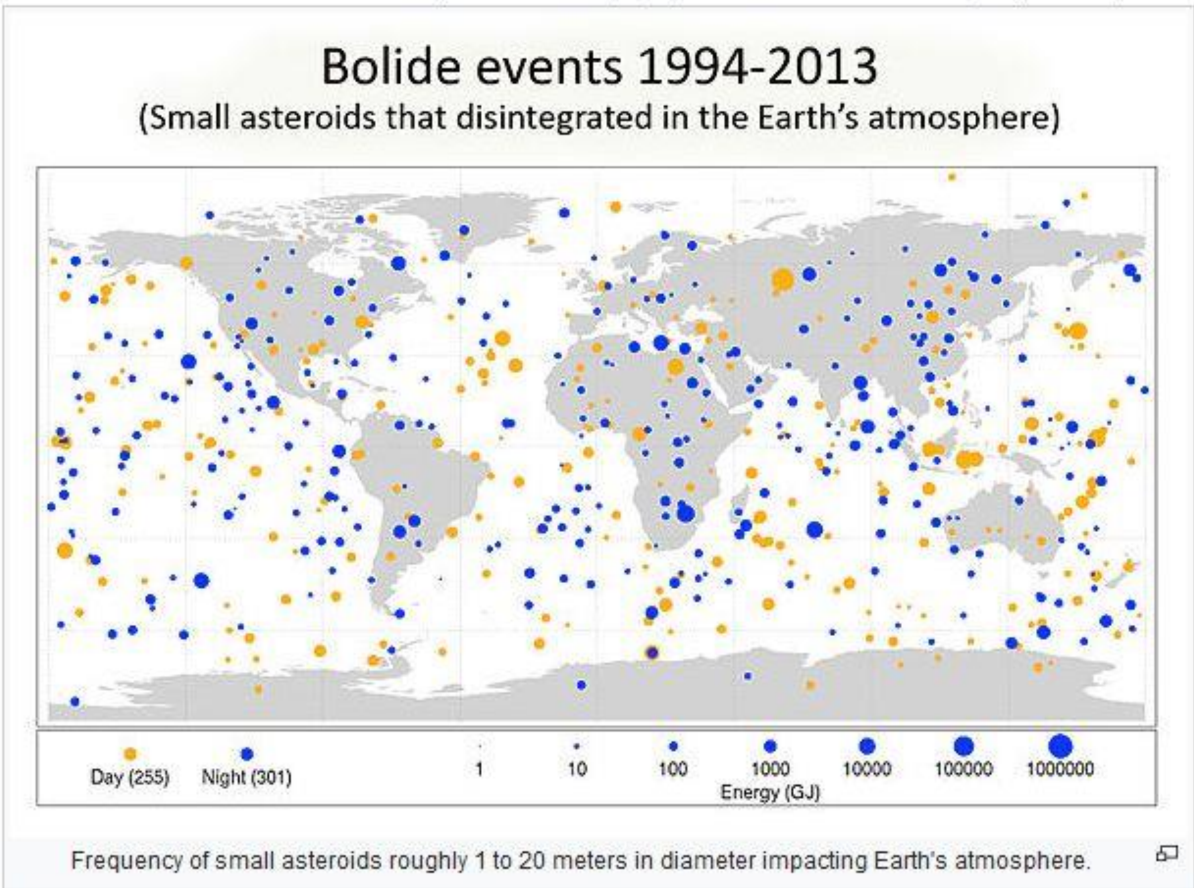


Figure 1. Impact with Earth's atmosphere or surface by small asteroids [9]

The emphasis in past endeavors has appropriately been upon engineering a sufficiently robust apparatus to conduct a singular mission to a pre-identified target asteroid and perform a pre-planned set of tasks including the retrieval of a physical sample and then returning this sample to either Earth or to a future lunar location for later retrieval. ASTRIC is based upon a different conceptual framework that deliberately takes into account likely internal system failures within units, short windows of time for meeting the threat with physical contact, a variety of mechanical failures at the point of contact with the target, and as an overriding principle, the need for being able to respond with multiple devices and multiple forms of interaction with the target. Thus, ASTRIC is conceptualized as a toolbox which in a conceptual "LEGO" fashion can come apart into different units and at times mechanically reassemble, and also employ different specific tools such as drills, solar-powered and RTG (radioisotope thermoelectric generator) powered lasers, methods for kinetic, ballistic and gravity-mass deflection, and a novel approach unique to ASTRIC, a net-and-tether system incorporating ultra-strength carbon-fiber cables and the use of the robot components as engines for application of mechanical directing force.

II. System Architecture Fundamentals

ASTRIC is designed to be multi-tasking and multi-purpose. This is an overriding philosophical base-point for an mechanical, electro-chemical, or computational sub-systems to be designed and deployed. The inherent imprecision about asteroid targets in general, for both defensive (impact avoidance) and constructive (mining, industrial) missions, is high and in spite of significant advances in remote characterization of composition, mineral content and basic tomography, time is always on the side of the asteroid, not the humans. Some targets may appear with only weeks or days for a response, if an ASTRIC base is in place and ready. This constraint pertains as well to non-defense, non-impact situations as well. An asteroid that may be an "optimal find" in terms of valuable metal or mineral composition, or possessing the capabilities for H2O extraction or chemical production, can appear with short notice. ASTRIC aims to have on hand, onboard, the capabilities to make contact, to manipulate, and to operate – such as with drilling, laser-cutting, and sample extraction – that will be needed for the tasks at hand. This implies also a long-term goal of having the capabilities, through modular robots and the use of reconfigurable tools including manipulators and engines, for retooling and remanufacturing of parts as-required for a long-term sustainable mission.

Missions are focused upon assembly, construction, manufacturing, mining and other engineering tasks. Principally these missions involve a number of cooperative robotic units and systems that are deployed to asteroids or other space objects in order to conduct physical tasks with those objects. Task types span from mining and processing of raw materials, to fabrication and assembly of mechanical structures, to deterrence of asteroid impact events by means of asteroid trajectory modification or other means.

At the heart of ASTRIC as both a deployable system of parts and as a design strategy within the project are two major components and divisions of labor. The <u>ASTRIC Mission System</u> (AMS) is a modular and reconfigurable set of robots and spacecraft designed to be customized for different missions. Its components include robotic instruments for manipulation of objects including asteroids and other natural and synthetic objects in space, plus the transport structures and devices required for mission deployment. The <u>ASTRIC Cybernetic Engine</u> (ACE) is a computational system designed for control of the components within the ASTRIC Mission System. Its architecture incorporates parallel distributed computing, network computing, and supercomputing resources, plus heterogeneous computing devices including the currently-in-development GCM (Generalized Computing Machine; a computer based upon topological forms of information representation and processing and employing a new approach to quantum computing and quantum information control) [2, 3, 4, 5]. The ACE enables modeling of complex and uncertain interactions among objects such as AMS robots and the target asteroids with which they are engaged in a mission. The GCM architecture employs adaptive synthetic intelligence algorithms including stochastic approximation, cellular network sampling, and randomized algorithms operating upon both Turing Machine and Trans-Turing ("quantum computer") devices.

Within the first generation of ASTRIC including the planned 2024-2026 period first launch of a demonstration system into either lunar or mid-range earth orbit, an advanced computing system as the aforementioned GCM may not be fully ready or even necessary for onboard inclusion, but its prototype(s) may be used from ground stations on Earth. In such case, sufficient supercomputing resources will be employed for tasks projected to exist.

As a control and decision system, ASTRIC is not limited to any singular mechanism for manipulation, construction, sampling, or propulsion. This is considered to be a critical feature in enabling the system to be adaptive to diverse categories of asteroids and to enable a diversity of responses rather than to be limited to only one physical, technical protocol. The overriding constraints are those of component packaging and configuration for launch and transport to an operational base (e.g., DSG) and the tactical operations to be conducted at a region of contact with a target asteroid. Several novel apparatus are currently being considered (refer to section IV below) and are being used in initial experiments focused upon terrain navigation and coupling between robot devices for such tasks as ensuring a sufficiently strong grip on an asteroid surface feature, in order to perform a task such as drilling or operation of a tether-and-net unit. Figure 2 provides an overview of the system architecture and the comprehensive technical plan underway, coordinated by the ASTRIC Laboratory being established within the Aerospace Technology Research Center at South Urals State University, in Chelyabinsk, Russia.

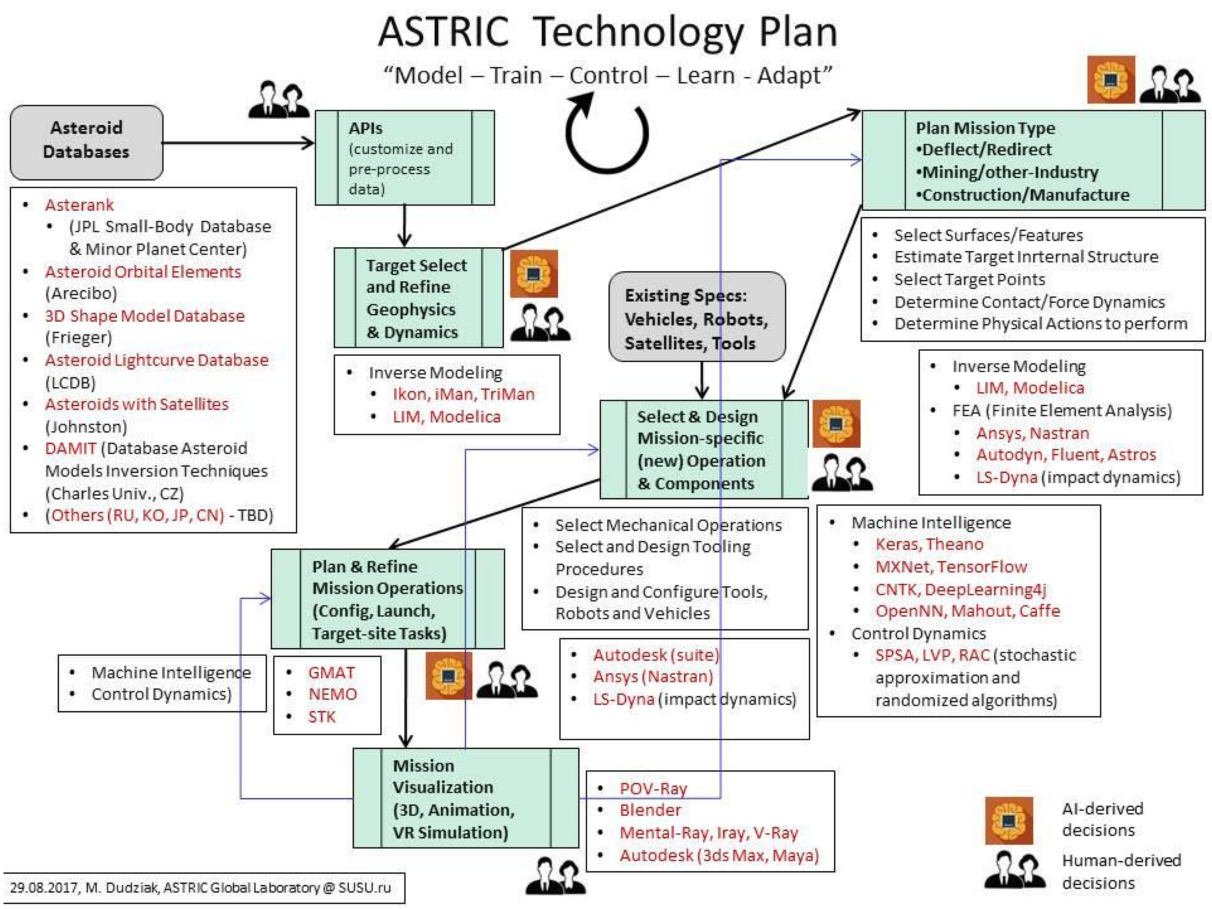


Figure 2. ASTRIC System Architecture Overview

III. Explication of the Architecture through the AMS Tech Plan

Each Mission involves a combination of sequential and parallel operations following the "algorithm" of the Technical Plan as presented in the previous section (cf. Figure 2). These segments of the Tech Plan operation are presented in the following set of figures combined with text annotations.

The AMS is constituted by five main blocks or phases. These are designed to accommodate any ASTRIC missions and this is a fundamental system design principle. The objective is to provide an architectural framework that employs common use-case and object-oriented process building blocks, a common concept from well-established software and electronic engineering, and through this mechanism to provide and sustain an ontological and epistemological structure for AI-enhanced reasoning components - thus, a common platform for the knowledge engineering that is deemed essential for enabling any system such as ASTRIC to function efficiently and reliably under naturally highly uncertain physical circumstances. All potential-threat asteroid appearances and behaviors cannot be well-studied in advance, regardless of telescopic and spectroscopic capabilities, since history demonstrates very well that asteroids may remain undetected until the proverbial "last moment" (as in the situation with both the 2013 Chelyabinsk superbolide and the virtually simultaneous "near-miss" fly-by of the *367943 Duende* object.

Each of these components is briefly described here. While to a certain extent they follow in sequence, they are also to be considered as iterative (quasi-interpolative) steps.

<u>Asteroid Selection and Parameter Refinement</u>

Any mission must be tailored to the specific target object. What is known or knowable about the target depends upon whether or not there has been any opportunity for prior (early) detection and observation. Five major databases exist which are accessible to ASTRIC. Real-time observations are acquired as well. Figure 3 provides a summary illustration. This component is charged with providing a dataset of as much comprehensive information about the target as possible, for use in determining the type, number and toolsets that the ASTRIC robots can use in an attempted trajectory modification, for instance.

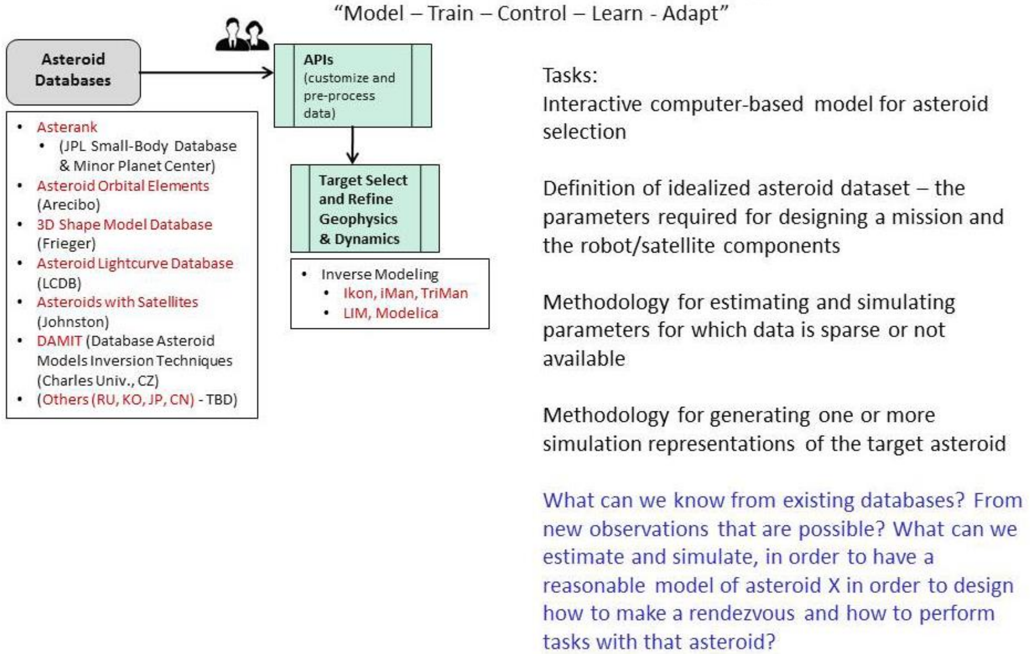


Figure 3. ASTRIC Mission component 01 – asteroid selection and parameter refinement

Specific Mission Typing

The second main component addresses the mission functions – what will be the optimal and required methods of performing trajectory modification, based upon the ASTRIC repertoire available for either earth-launch or orbital/lunar deployment. Figure 4 provides the summary description.

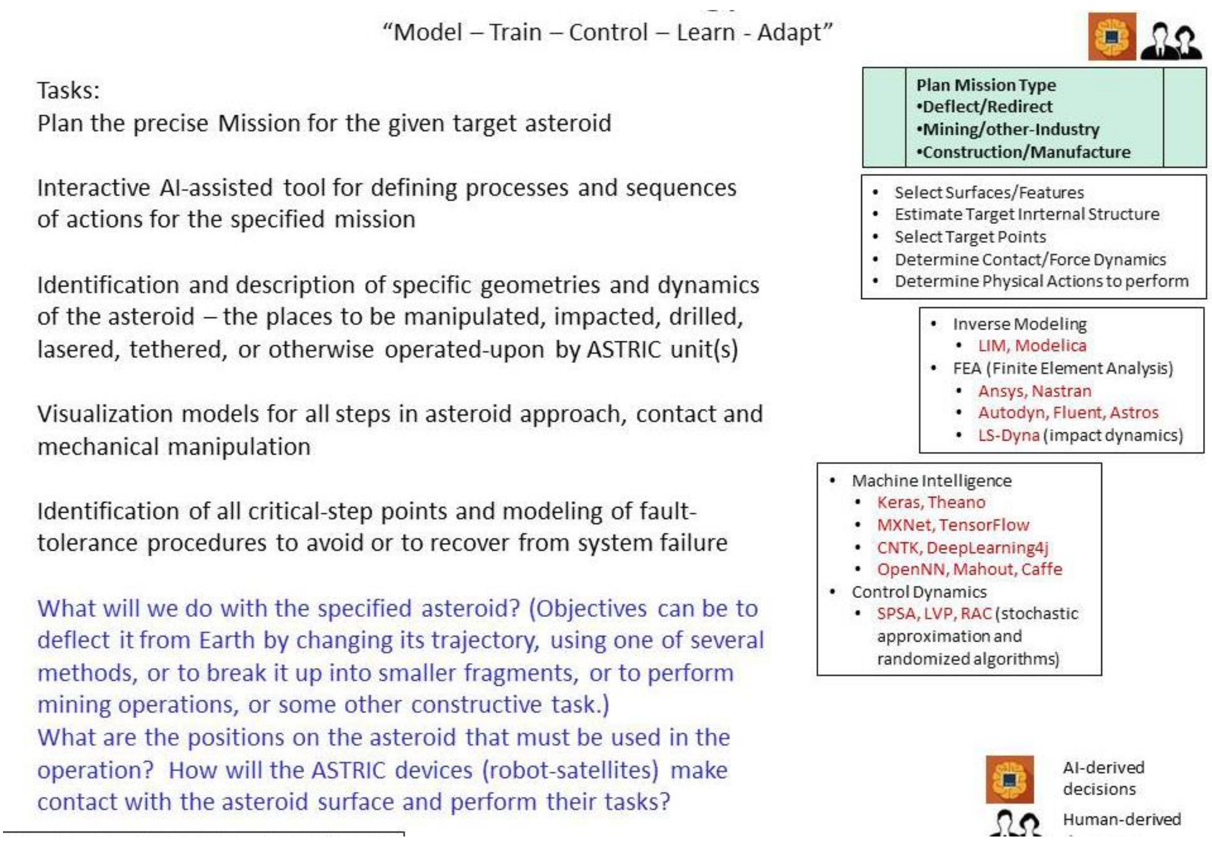


Figure 4. ASTRIC Mission component 02 – Specific Mission typing and parameter setting

Mapping Specific Devices to Specific Operational Tasks

Given the known specific properties of the target, and the robotic tools that will be employed on a given mission, the next task is to define how the tools will be employed at the target site. A significant part of the work in this phase is in fault tolerance and recovery planning. Presumably there is no time for a "second chance" (i.e., launch of alternative machines). Figure 5 provides a summary of the actions. A key part of this process is in comparing simulated outcomes of different tasks, including failures, between the ASTRIC robotic units and the estimated target object.

Configuration of Launch Operations and Target Acquisition

The fourth main component is described in Figure 6. This is the major system integration process, and this is where the "interpolative" and "iterative" process elements apply. Only after a tentative system architecture has been configured and simulated will it be possible to examine through simulated maneuvers all the expected variations and responses to uncertain conditions. It must be kept in mind that the target asteroid is quite likely a newly detected object and not one for which there is ample and sufficient knowledge prior to the necessary launch of the ASTRIC system.

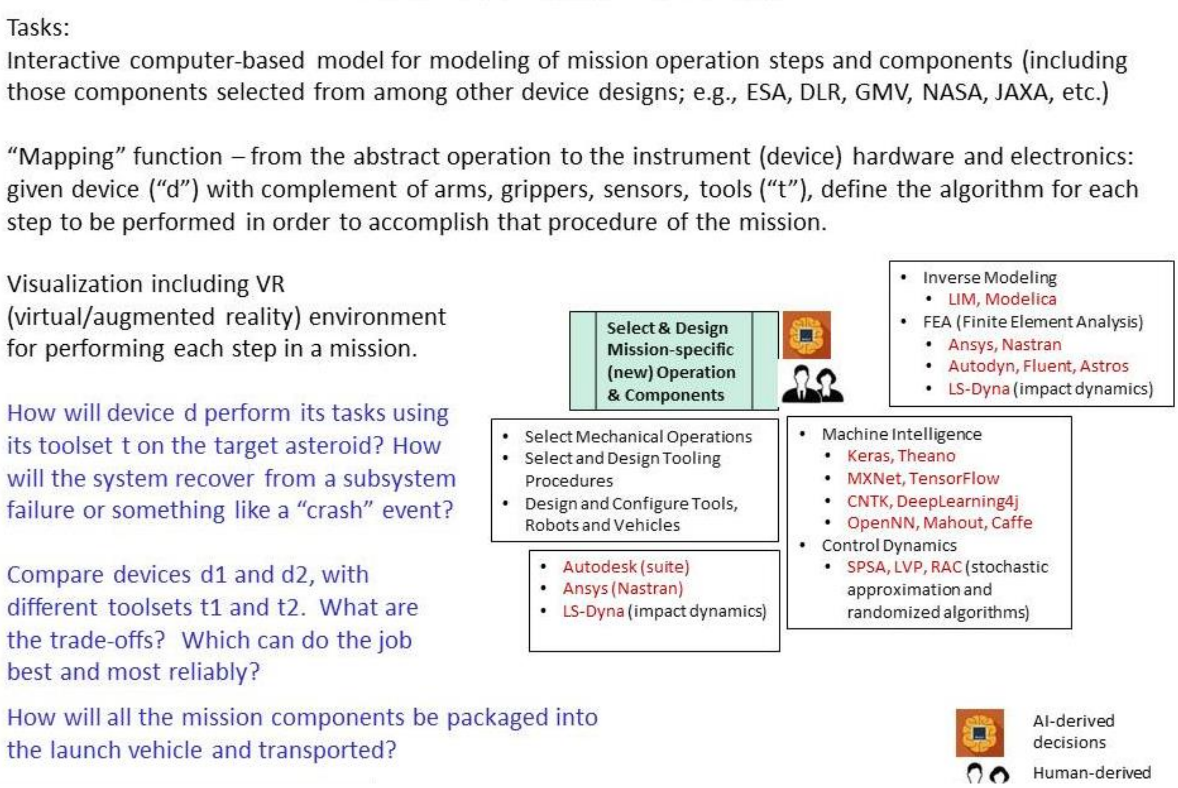


Figure 5. ASTRIC Mission component 03 – Mapping device tool units to specific operational tasks

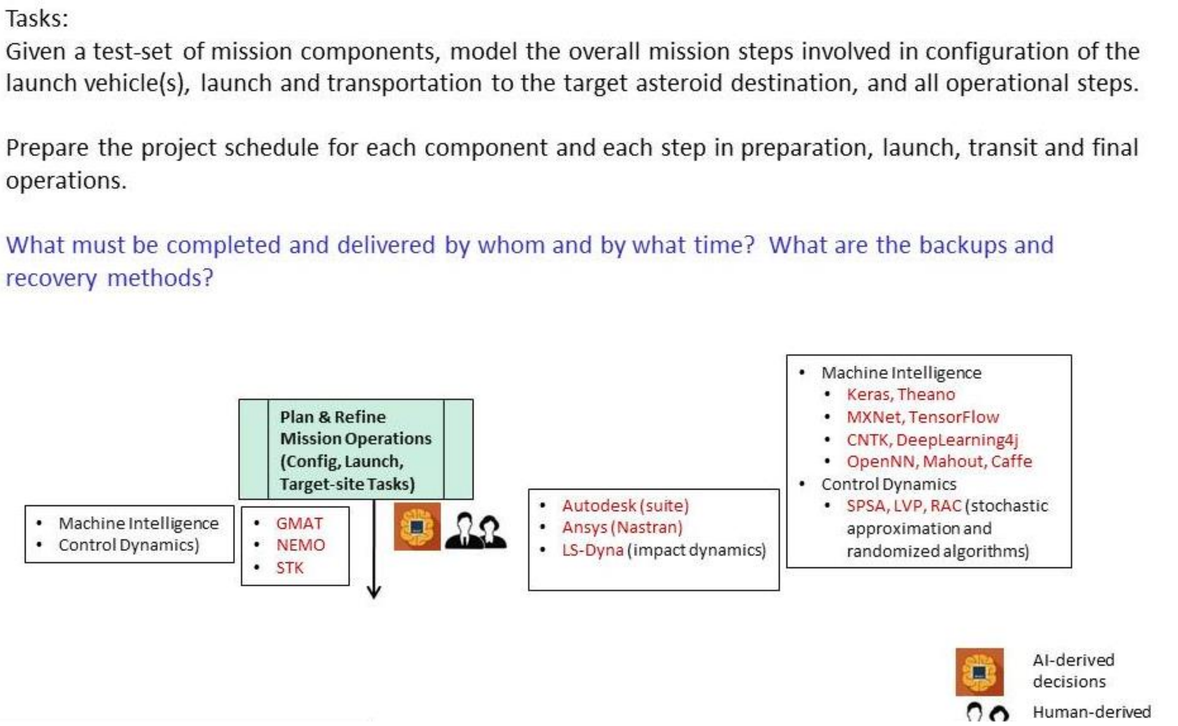


Figure 6. ASTRIC Mission component 04 – Configuration of launch vehicle, launch operations and self-transport of system to target reconnaissance and contact point

Visualization, Animation and Human-Robotic Interactive Control Processing

This component is one that begins from the very outset of the AMS planning activities, but it reaches a stage of completion only after the prior stages have been executed. The results of these visualizations will enable engineers and operators to iterate again through some of the earlier AMS modules. Figure 7 provides a summation.

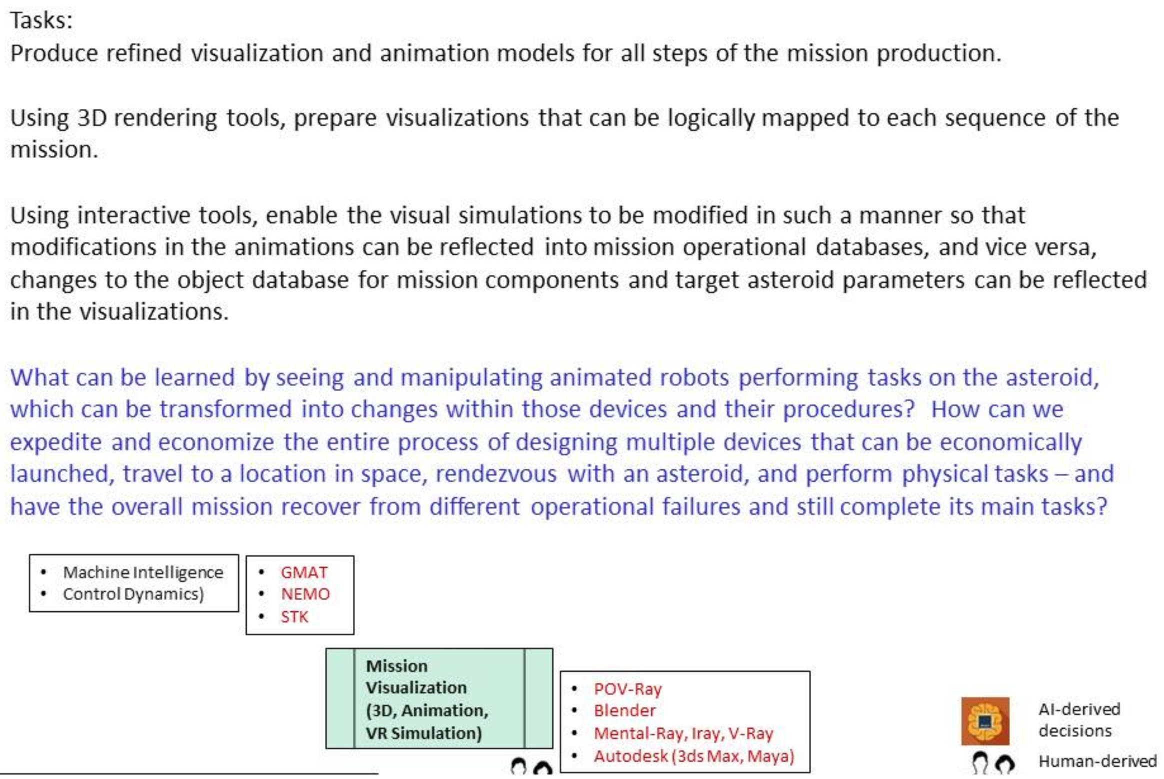


Figure 7. ASTRIC Mission component 05 – Visualization and animation production for enhancement of human and robot-assisted mission action planning

IV. Variant manipulator "species" types for robotic components

Characterization of asteroid lithography and surface features is extremely challenging due to the limited data available by optical or other spectroscopy. This is exacerbated by factors of time availability in the case of asteroid objects that may be detected virtually "last minute" with perhaps, at best, days to plan a response mission. Within that timespan must be calculated which available units will employ what types of response mechanisms. Clearly one tool and one method will not fit all needs, and the main objective of ASTRIC as a system is to provide multiple methods to use on any given asteroid and to be suitable to address multiple types (sizes, lithologies, geologic and mineral compositions). It should be kept in mind that ASTRIC is intended, from the standpoint of both engineering and as an economic endeavor, in its research phase and subsequently in its deployed operations, to also serve non-defensive, non-impact related interests concerning asteroids; i.e., asteroids as artifacts to be employed in mining for mineral or water extraction, or for other uses such as a base for solar power stations, for habitation, or as a way station for interplanetary spacecraft.

There are several categories of robots currently under evaluation for use in ASTRIC operating environments. These derive from prior work by partners in the consortium including the Russian Scientific Center for Robotics and Technical Cybernetics (RTC) and the St. Petersburg Institute for Informatics and Automation of the Russian Academy of

Sciences. These include modular robots with reconfigurable, re-arrangeable and replaceable units, multi-axis serpentine robots for all-terrain navigation and gripping, and multi-arm interchangeable manipulator-gripper robots, one of which has been designed expressly for use in the International Space Station and it is scheduled for launch in 2018.

Figure 8. RTC Modular Robots for high-unpredictability surface geometries and textures

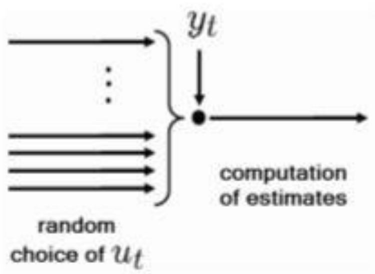
Figure 9. RTC Multi-axis, multi-arm, self-interchangeable gripper-manipulator robot (ISS selection)

Figure 10. Soft-armed/legged robot for multi-point flexible and secure gripping [from Laschi, 11]

V. Control Logic Foundations

At the heart of control issues for complex systems with non-deterministic qualities and potentially NP-hard computational barriers is a set of methods that have been demonstrated across many fields of application to offer accuracy, low-risk and speed, all of which are critical for ASTRIC. These involve simulated perturbation by stochastic approximations (SPSA), local voting protocol, and randomization algorithms. The employment of SPSA is directed at both reduction of the state-space search and avoidance of errors by virtue of not taking into account new relations among system parameters that heretofore were deemed to be not significant (or weighted sufficiently) – a problem of non-linear outliers and anomalies.

The Local Voting (LV) control protocol developed by Granichin et al [6] is one such model. It operates with a nonvanishing step-size for conditions of significant uncertainty and external disturbances [14]. The objective is to detect changes that may be insignificant in most cases but which can be indicative of developing conditions that could have irreversible effects. This stochastic gradient-like (stochastic approximation) method has also been used before in other works (see, e.g. [15]) but with a decrease to a zero step-size. Usually, the stochastic approximation is studied for unconstrained optimization problems, but the above-mentioned results stimulated the development of new approaches [20] to track the changes in



the parameter drift using the simultaneous perturbation stochastic approximation [21].

Figure 11 – Random selection of estimation and control coupled with learning and optimization [6]

An experimental platform has been developed [6] (Figures 12-15) which addresses one major problem in aerodynamic stabilization during turbulence, focusing upon wing surface pressure points as the key observable parameter. This may be considered as a prototype for use of the LV protocol to other applications including the interactivity among a group of cooperating robots, or the dynamics of one or several robots manipulating an unwieldy, relatively amorphous and free-standing object, such as an asteroid or other object in low-gravity or zero-gravity (e.g., "space-debris" in near-earth orbit). Thus, we are applying a technique demonstrated to be effective in aerodynamics, for a qualitatively different type of turbulent mechanics, albeit not in air or a fluid but operating in mechanical contact with other robots and with a central asteroid target. In such a case the "turbulence" is not present in a classic aerodynamic or hydrodynamic phenomenon but there are comparable dynamics in the forces exerted between the target object and the robot apparatus operating with it. Simple joining of satellites, robots, and manipulation of fixed-geometry parts in zero-G space offers challenges that are "extreme" in comparison to those in an earth-gravity or planet-gravity region, and the demand for computational simplicity and speed (other than what can be provided by impractical "supercomputers" or machines requiring cryogenic environments (e.g., contemporary "quantum computers") becomes mandatory.

Within ASTRIC operations there are critical time intervals for such adaptations that can avert an critical "singularity" event affecting the entire complex system consisting of robots and the asteroid unified within the state-space. Randomized alterations to small regions (clusters) of the system space have two unique advantages over models that attempt to comprehensively address the entire system. First, results can generally be achieved faster and with fewer computational resources. This is significant for mobile, remote and compact device platforms (such as satellites and other space vehicles, robotic or otherwise). Secondly, and very significantly, errors in the decision process – which can be frequent in beginning stages of a cybernetic system adaptive learning process – will be more localized, more containable, and more easily correctable, than errors which affect large sectors of some system performance.

VI. Conclusion

ASTRIC is in its early phases of development and prototyping. There is a clear and present need for a robust, modular, fault-tolerant system that can be deployed rapidly – within days at the most in some cases – even, ideally, within less than 24 hours notice. Not all impact-threat asteroids come with a “calling card” that identifies their threat capability by decades, years or even months. Currently there is no systemic approach for asteroid-threat mitigation that addresses the needs for real-time, post-launch, “on-the-fly” versatility and reconfigurability. Fault tolerance – indeed, “fail-safe” – is essential when there may be only one chance for solving the problem millions of kilometers away from any earth-based or orbital alternative. ASTRIC proceeds forward, one step at a time. *“Ad astra per aspera.”*

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