# Project ASTRIC and Project TETHYS - coordinated uses of space-based resources for dual applications in terrestrial environmental forecasting and space-based operations of terraforming and asteroid operations

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Abstract

This paper describes work in progress within two projects that both focus upon coordination of cooperative autonomous robots and sensing systems. One project, ASTRIC, began with a focus upon improved control and comprehensive cybernetics for missions involving diversified and cooperative robots to perform physical operations with asteroids and other space-based assembly, construction, mining and manufacturing tasks. The other project, TETHYS, relatively newer in onset (2019), focuses upon similar tasks within space-based and terrestrial sensing, sampling and monitoring within lakes, estuaries, wetlands, and watershed regions. The two projects have commenced to be integrated into a comprehensive program as a result of common architectures and platforms for both physical hardware and the algorithms and software employed in stabilization, navigation and cooperation. The work is underway among researchers in USA and Europe including Michigan Technological University, Great Lakes Research Center, Inland Seas Educational Association, and partners in several institutions in Europe. Presented here are foundational and conceptual bases, and current work-in-progress, leading to the ensuing next phases.

## Introduction

During the course of initial research focused principally upon issues of system control and cybernetics, particularly in the context of multiple species of robotic machines and instruments operating at significant distances and often without the possibilities of real-time or near-real-time human intervention, it became clear that there are excellent opportunities to perform not only computer-based simulations but prototype experiments in earth-based environments. The goal has been to satisfy the need for improved fault-tolerant and indeed fail-safe operations that can be performed in distant space while affording more accessible testing and experimentation, and all in a manner that will satisfy other important needs of the scientific community that concern immediate-at-hand challenges that will require cooperative and intelligent machines. These other needs concern the terrestrial environment in the face of climate changes and nonlinear, extreme behaviors, resulting in a natural adaptation to which humans must themselves as a society, learn to better forecast and understand.

ASTRIC began as a research project in cybernetics and control systems for cooperative and heterogeneous robots to operate autonomously or with minimal or delayed human-machine interaction. Its focus has been on asteroid manipulations including trajectory modification for asteroids that may be 100m or larger in approximate diameter and with orbits deemed to pose a significant probability of impact with Earth or future human habitations on Moon or elsewhere.

TETHYS is an Earth-focused project in environmental monitoring and forecasting focused upon freshwater lakes, inland seas and watersheds for modeling and prediction of large-scale long-term biosphere and limnological changes related to climate change, permafrost melting and industrial pollution. Space-based satellite resources form an extensive set of components for data collection. Robots and control systems developed for future

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space-based operations (ASTRIC) are being designed and tested in marine environments, furthering the dual-use and bidirectional resource utilization objectives. Flexible-arm, multi-axis and self-modification robots with multi-tool capabilities are being applied to use in terrestrial (environmental) tasks in ways that enable their application to space-based operations with asteroids and also lunar or planetary surfaces.

What follows here are three sections, principally in the form of illustrations and figures. First, the basics of ASTRIC control architecture and project plan. Second, the overall description of TETHYS and initial plans for a pilot program within TETHYS. Third, remarks on how these serve each other and the important areas and concerns regarding effective, economical, and multi-purpose uses for space resources, both existing and future types.

There is a fundamental philosophy underlying both Projects and the integrative Program that now unifies them. This is expressed in terms of four optimization goals that aim to satisfy the following:

[1] Operational implementation as rapidly as possible, given the combinations of probability (of occurrence) and uncertainty (of intensity and impact) for mass-impact, mass-effect events affecting, essentially, all of human civilization. In other words, we are not dealing with a situation that is perhaps of scientific interest but of no significant consequences to humanity as a whole, should the research and development not be conducted and implemented into working productive systems. This applies to both ASTRIC and TETHYS.

[2] System ability – technically and economically – to do things efficiently, rapidly, but also with accuracy. Another optimization function, one that is in respect to both the "mechanics" (the actual science and engineering) but also the people, as individuals, teams and organizations including governments and corporations.

[3] Fault-tolerance and fail-safe principles carried to a maximum. If a mission consisting of a fleet of robots is tasked with modifying the trajectory of a given asteroid that has high probability of impact with Earth, there will almost certainly be no second chance, nor opportunity for a "later mission" in several years' time. Our turn-around in such missions must be radically improved from everything that has been the case to date with long-distance and interplanetary satellites, rovers, telescopes, and other missions. Observing the surface of Mars or the distant reaches of the universe can wait for another time, for years if necessary. Asteroid diversions cannot. Similarly, on Earth, having in place sufficient multispectral systems of data collection and integration, for making more accurate forecasts of how freshwater bodies will react to even single-digit average temperature changes over single-digit annual timeframes, and how this will impact food chains, invasive species proliferation and food supplies, is not something that can be put off indefinitely. The need to know and to know how to act accordingly is upon us as a civilization.

[4] Education at multiple levels and for open socioeconomic spectra. In all of this, we regard education as a critical component, and specifically STEM (science-tech-engineering-mathematics) education among youth and the general population. In both of these broad areas of space development including planetary defense, and environment change and adaptation including climate variation, it is of foremost importance to develop broader, deeper, and more accurate education for not only "future generations of scientists and engineers" but the complete, general population of human beings. Without such attention to inclusion and education for all, there can be only failure and disaster in the future events, absolutely forthcoming but at what dates and in what details we cannot predict, of traumatic and potentially cataclysmic events such as asteroid collisions and massive extremes in weather and climate effects.

## ASTRIC

Project 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 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, three 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, marine environmental monitoring, and intelligent agriculture ("smart farming"). The basis for this choice is twofold and can be summarized as follows:

(1) Certain mechanical and especially multi-unit, multi-surface tasks are such for both navigation, sensing, monitoring and constructive/destructive operations within mines, and in maritime subsurface searches and sampling (e.g., benthos, plankton, other micro-flora/fauna) 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, marine sensing and monitoring, and climate-adaptive 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.

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 radically 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.

## System Architecture Fundamentals

ASTRIC is designed to be multi-tasking and multi-purpose. This is an overriding base-point for all 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 re-manufacturing 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 ASTRIC Mission System (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 ASTRIC Cybernetic Engine (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, 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 1 provides an overview of the system architecture and the comprehensive technical plan underway, coordinated by the ASTRIC Laboratory established within the Aerospace Technology Research Center at South Urals State University, in Chelyabinsk, Russia.

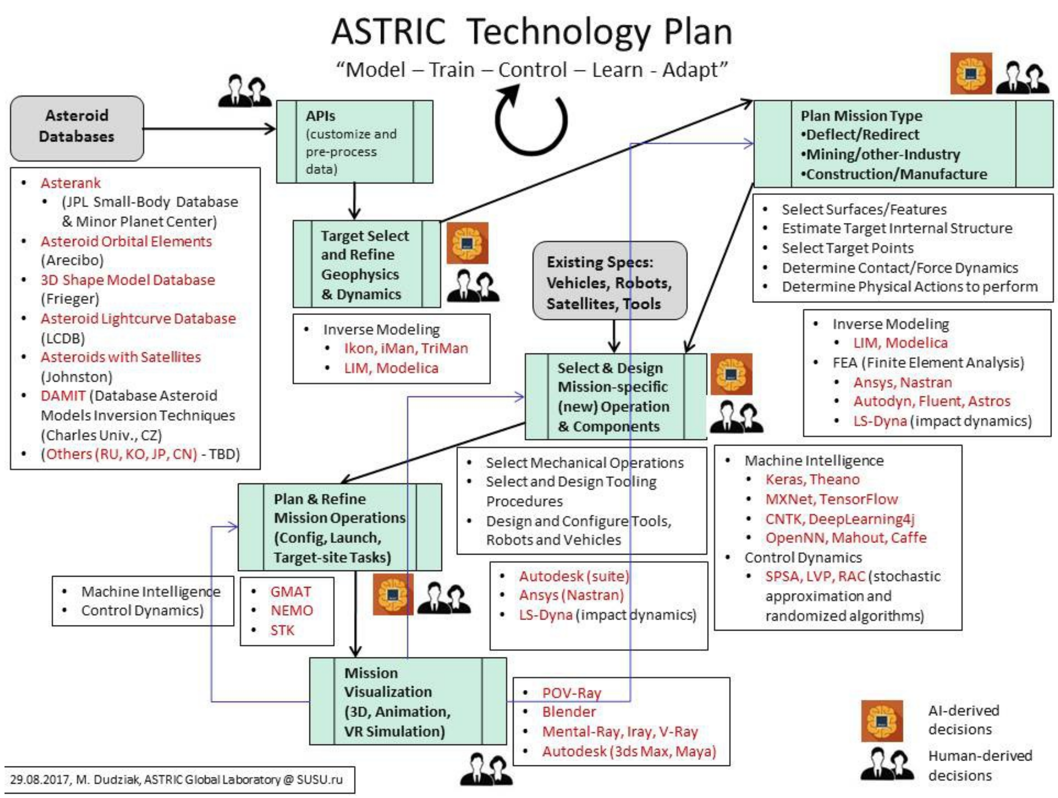


Figure 1. ASTRIC System Architecture Overview

Figures 2 and 3 below provide further illustrations of the technical design process for both the AMS and ACE.

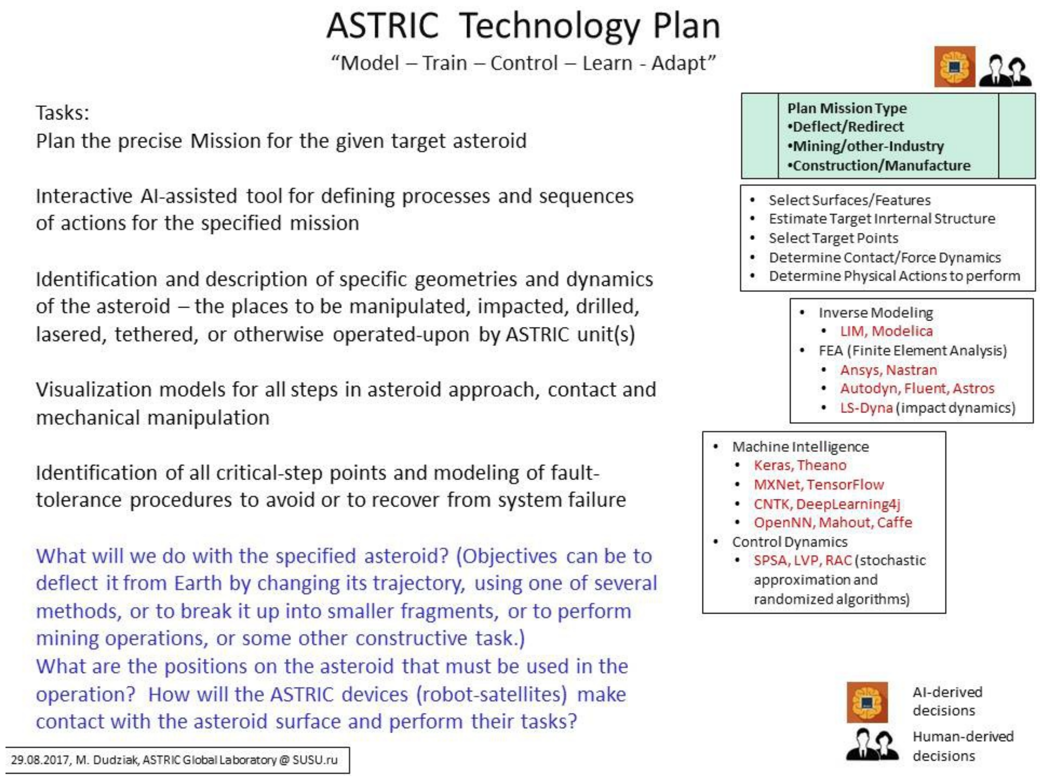


Figure 2. ASTRIC System Architecture Development – Task 2

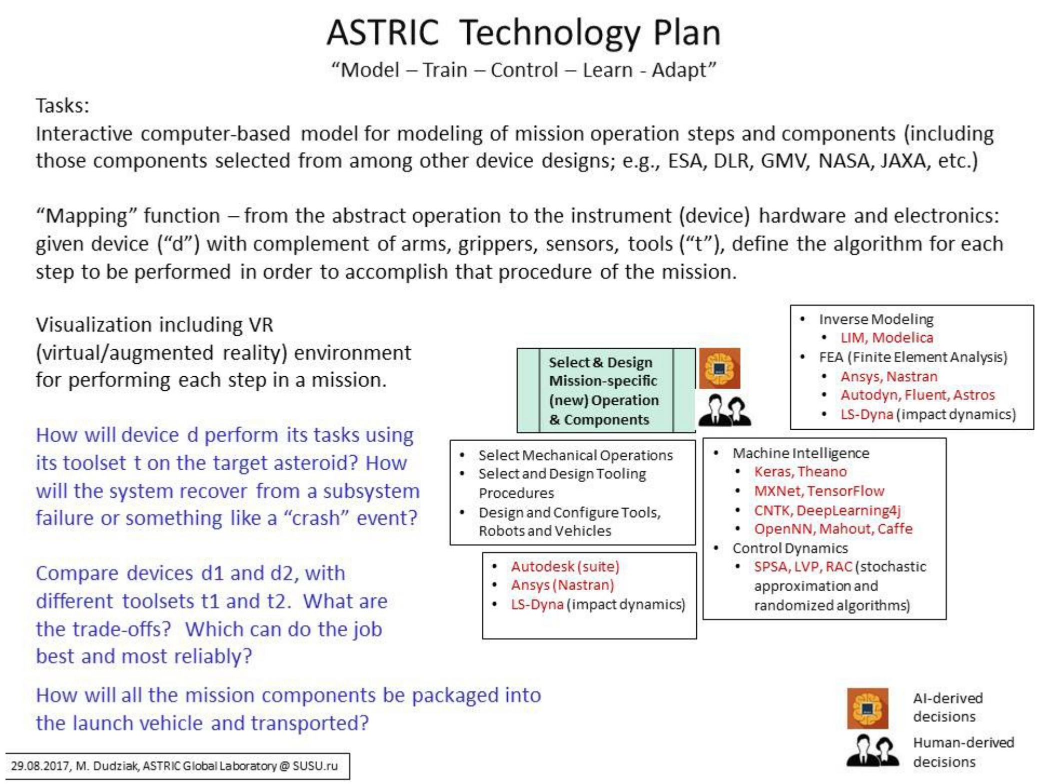


Figure 3. ASTRIC System Architecture Development – Task 3

## TETHYS and the LETO Mission

Project TETHYS is a research program in search of the right questions and then the right answers for how we can employ our planetary freshwater lakes and streams in the best ways to sustain life on Earth in the face of inevitable, progressive and probably changes which could threaten human and other forms of life.

Climate change and aspects of its current progression are difficult to predict. There are other threats to organized human life and life in general that may come from within the Earth or from beyond it, and in most cases the effects on freshwater bodies will be dramatic. In many cases we cannot prevent certain events and consequences that will follow. In most cases we can hope to adapt and do our best. TETHYS aims to produce the best toolsets of knowledge and skills for optimizing the outcomes in favor of survival and sustainability.

TETHYS examines what we have been studying – our datasets, our methods of analysis, and our processes of modeling and forecasting. Its objectives are to consider what we have available and what is feasible, in the way of technologies, and to employ them more effectively, most effectively, so that the ecosystems of freshwater bodies such as major lakes and river systems around the world can become a *multi-dimensional "barometer"* for what is also transpiring and changing elsewhere on our planet, including in our mid-continent regions, our deep oceans, and in the interfaces between earth, water and sky that determine how our crops will grow, how maritime food sources will be maintained, and how the changes imposed by our changing climate will affect our water and soil and air in the future. As one example, TETHYS will study, using resources that are orbiting in space, airborne, on the surface and also subsurface, the changes in persistent organophosphate pollutants that are being released from thawing and melting permafrost regions and subsequently deposited on our soils and in our waters.

Project TETHYS is organized as an independent consortium of people and institutions. It is coordinated and managed by The TETRAD Institutes, a private not-for-profit research organization. The consortium is (as of September 2019) in the process of being established among several institutions, including:

USA (Michigan Tech University, Univ. of Minnesota, Univ. of Maryland, Colorado State Univ.)
United Kingdom (Univ. of Surrey, Strathclyde Univ.)
EU (Denmark Tech Univ., Norwegian Univ. of Science and Technology, Pisa, Barcelona, TU-Delft)
Switzerland (ETHZ, EPFL)
Russia (St. Petersburg State Univ., Central Research Institute of Robotics and Technical Cybernetics, South Urals State Univ.)

TETHYS activities are principally a new set of uses and applications for what many research programs have been producing and are continuing to do in the course of their established activities. New project activities are designed to make the most use of what is already in place and ongoing (e.g., continuity with existing AUV/ROV data collection, Copernicus/sentinel satellite telemetry, and established projects in the development and testing of sensors, robots and simulation systems. This enables the operation of analytical and computational laboratory functions that are concurrent and non-intrusive with existing projects and assignments, in essence adding value and utility to existing centers. TETHYS provides simultaneously an active network-based research facility for scientists and a highly visible educational experience for non-specialist visitors, volunteers and the general public through a variety of media and direct-encounter opportunities. All of these functions and measures of engagement derive from what participating institutions and team members have been doing already and what has been demonstrated to be feasible, viable and successful in other venues.

TETHYS is focused upon the comprehensive history, present conditions and potential futures of freshwater streams and lakes and the ecosystems that exist and evolve in the proximity of such freshwater bodies. The primary focus of TETHYS experimental work is upon several inland seas in North America, Europe and Asia, with defined plans to expand activity worldwide to all continents and oceans. The foundations of TETHYS enable integration of data, information, knowledge and experience with a global community that is concerned with and addressing common issues and concerns for freshwater environments and habitats worldwide. This is an important and integral function of Project TETHYS – bringing people and knowledge together in order to optimize the ways we work with our lakes and streams and water supplies, for our society and its economy, stability, and sustainability. Thus, the STEM education and engagement components, for youth and students, is deemed essential, and this includes specific internships and apprenticeships at all competency levels.

The laboratories involved in TETHYS enable scientists, engineers and technologists from the academic, corporate and public communities to participate in scientific investigations that encompass analytical chemistry, analytical microbiology and computational modeling and simulation. Mobile laboratory units, including trailers and containers, are extensions of the primary "virtual lab" network. These mobile units are principally employed for data acquisition and for education/training and public awareness/experience, using existing research vessels and other appropriate marine, terrestrial and aviation vehicles.

The space-based components within Project TETHYS are closely-coupled with prior and ongoing research and development comprising the ASTRIC Project. ASTRIC has historically been focused upon the design and deployment of intelligent cooperative robotic systems for deep-space (beyond Near-Earth Orbit) operations such as in the modification of the trajectory paths of potentially impact-threat asteroids. Part of TETHYS operational planning is intended and designed to provide for the simultaneous use of novel robotics including micro-sized, soft-arm, serpentine and hyper-multi-axis robots, in aquatic environments such as deep lakes, for sensing and monitoring operations, and also for testing of prototypes that will be deployed, as part of the ASTRIC project work, in cooperative robot networks that perform tasks in space (such as mining, grappling, charge-setting, and other tasks) with asteroids and on other orbiting and transiting bodies.

TETHYS aims to produce an effective and rapidly verifiable model using the *Inland Seas as Barometers for Planetary Sustainability through Nonlinear Environmental Change*. This spans more than standard climate change issues; the range includes: Climate Change including release of pent-up (permafrost) pollutants and CH4, Volcanism, Asteroid Impact, and Human Destructiveness (overpopulation, over-industrialization, CBRN pollution, nuclear war). Project Units and Components of TETHYS include space-based monitoring via Copernicus/Sentinel, TETHYS Cubesats (monitoring of POPs and other chemical pollutants from melting permafrost regions transferring into lakes, wetlands and agricultural regions), and the use of ASV, AUV and UAV. The environmental range of Marine Surface and Subsurface Monitoring spans: Freshwater Lakes, Estuaries, Coastal Wetlands, Lake Watersheds. Land-based Monitoring focuses upon estuaries and wetlands, using UAV and UGV as well as direct human monitoring.

In order to effect a successful long-term development of TETHYS, a specific pilot project has been established. This enables the design and testing of the entire systems approach. It is known as LETO.

## LETO Mission (Superior-Alpha)

Cooperative Autonomous Air-Surface-Underwater Vehicles performing multi-function multi-sensor surveys and searches, with Autonomous Remote Recharging Operations, in the central Lake Superior Environment.

One of the purposes of the LETO Mission is to provide a succinct, concrete, specific and localized project that embodies many, if not most, of the attributes of what is common to both ASTRIC and TETHYS, especially regarding cooperative versatile autonomous machines which can be employed and can evolve directly for TETHYS and also for ASTRIC. This is: Testing and Doing on Earth what we will need to be able to do in Space.

Primary Operation Mission: The close vicinity to Stannard Rock in North America's Lake Superior. At this location can be located and operated the autonomous recharging platform known as the Delos Station.

Primary Monitoring Operation Mission(s): Environmental monitoring of lake surface and subsurface and bottom, including tasks already underway by the Great Lakes Research Center (GLRC) at Michigan Tech University. (Note that the locations in Lake Superior for these mission tasks could vary from those chosen for the primary search operations and also for the primary maintenance and support operations.)

Primary Maintenance and Support Operation Mission: Autonomous recharging and reprogramming of the ASV, AUV and /or UAV units at a mobile base capable of serving all vehicle types simultaneously and in sequence, employing a group of cooperative autonomous vehicles and a mobile floating base station ("Delos").

Secondary Monitoring Operation Mission(s): Ad hoc, non-pre-programmed and unsupervised detection and tracking of "interesting objects and behaviors" (e.g., presence of an unplanned and unknown-in-advance other surface vessel, submersible, or airborne machine) for demonstration of additional capabilities for the Leto Network of autonomous vehicles.

Leto Network – the Robot Fleet:
Full (goal) servicing capability (initial season and experiments will be for only ASV):

Four to eight ASV, recharging 1 or 2 at a time
Four to eight AUV, recharging 1 or 2 at a time
Two to four UAV, recharging 1 or 2 at a time

Robot Vehicle Types:

ASV – jet-ski unit used previously at MTU and others (non-tethered)
AUV – IVER unit used at MTU or others (non-tethered)
UAV – Parrot line of quad/octo copter devices, and also others that may be custom-designed

Robot Operations (in general):

- Searching with sonar, lidar (ASV, AUV)
- Searching with visible light, infrared, and SAR (synthetic aperture radar), as well as various onboard chem/bio sensors (UAV)
- Subsurface manipulations using mechanical arms (AUV)
- Communications relay among robotic and human operational platforms (e.g., ships) (ASV, UAV)

<u>Mobile Base DELOS</u>

Delos is a key component to the Leto Network. Its purpose is to provide an at-sea base for recharging and emergency landing of one or multiple units within the robot fleet constituting the Leto Network. The Delos design is intended to enable staged evolution and upgrading of capabilities from one or a few ASV to then also handling AUV and UAV. This enters into the long-term design of the base as a physical sea-going platform.

General Specifications:
Octagonal structure, approx. 4m "diameter" (width between opposing edges)
Basic frame construction is a composite structure of steel, aluminium, fiberglass, plastic

Tethering and stabilization is by anchors or a buoy mechanism or both.

Vessel mooring:

- ASV berths with a connector that upon contact becomes locked and is flexible under electronic control, with the net effect being similar to mooring bumpers in action. When contact is firmly established, the male/female couplers lock-in and later can be released under vessel or station autonomous control.
- AUV berths with a similar type of connector but from the underside, in the same way as an ASV.
- UAV berths by landing on the wide open ring area between the central hub circle and the perimeter. The UAV lands and couples, and with its landing feet on the deck, an electromagnet is activated to

assist in UAV stability on the deck. Sudden and extreme inbalance causes the UAV to automatically break the connection and go airborne.
- Manned vessels berth in a conventional manner.

Manned operations on Delos:
Delos Station is intended to operate unmanned and for extended durations. There are fittings for enabling mooring of a small outboard vessel (e.g., Saturn Inflatable 12' Dinghy Tender or Zodiac Inflatable Cadet 230). When personnel are aboard Delos, they operate on the “deck” (working surface area, inside lifelines onboard).

Electrical power generation onboard Delos:
- Photovoltaic generation
  - Si-based solar-cell panels
  - Polymer photovoltaic surfaces
- VAWT wind turbines (locations either on perimeter or in center region of the base platform)
- Wave-action generators, submerged below the Delos platform.
- Hydrogen fuel cell (for backup, and also for low-consumption times when more power can be generated than is consumed or than can be stored in onboard batteries)

Electrical power consumption:
- Requirements per each individual ASV/AUV/UAV
- Requirements for Delos system operation (communications, lights, pumps for any platform submersion operations, component heating/de-icing, etc.

Operating location and general at-sea operations:
Offshore Stannard Rock and close to the Reef, in order to enable access by AUV. However, Delos could be moved by ship (e.g., towing, LOLO or breakbulk) or helicopter to various locations as well as to land-based sites for maintenance or modification. ASV and AUV will have missions to search for particular features and objects using onboard sensors and communications with computing systems and human operators (who may be nearby onboard ship or in the lighthouse or in remote locations (e.g., @ GLRC, at MTU). Operating from April to early November, for Lake Superior.

Direct Connection To SPACE robotic applications:
Here are two examples of robots being configured and programmed for use via LETO in a marine environment, with specific modular control software design for operation later in asteroid missions as part of ASTRIC.

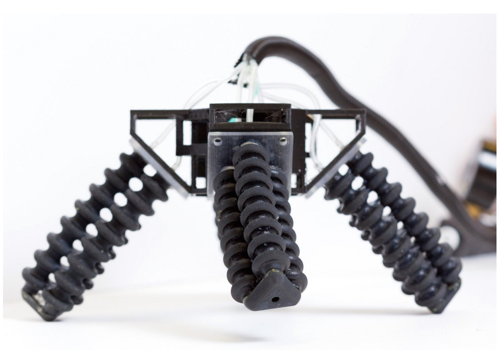

Figure 4. Soft-arm robots for marine and orbital cooperative manipulations [9, 10, 11, 12]

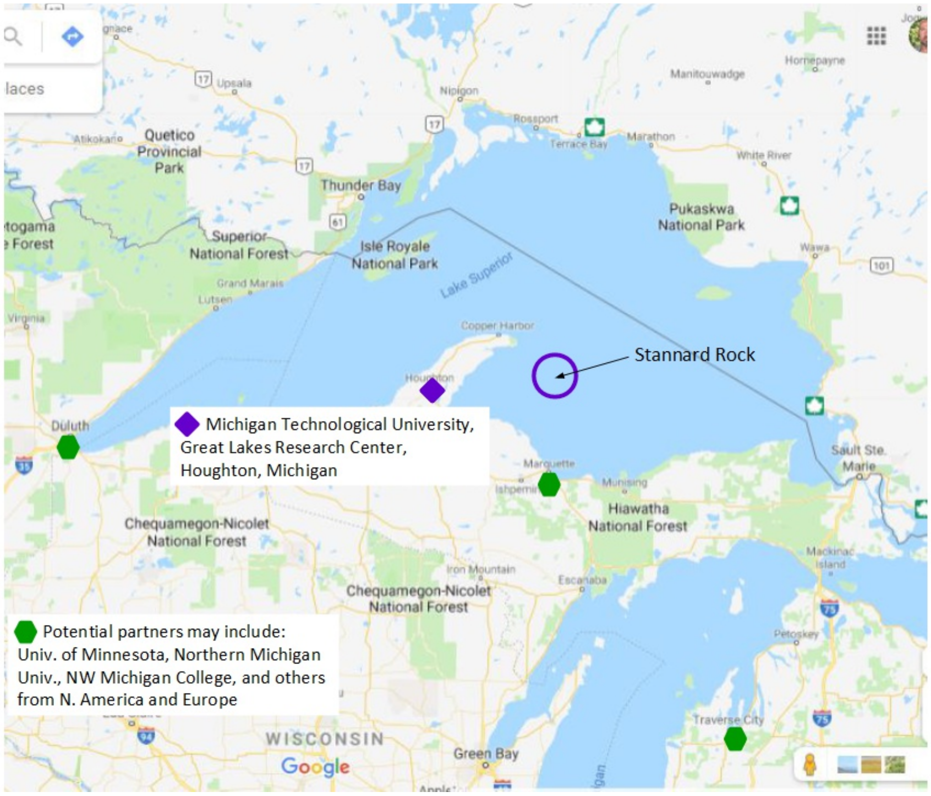


Figure 5. Lake Superior and Environs, showing location of Stannard Rock testing location for LETO


Figure 6. Map of Keweenaw Bay and region east including Stannard Rock

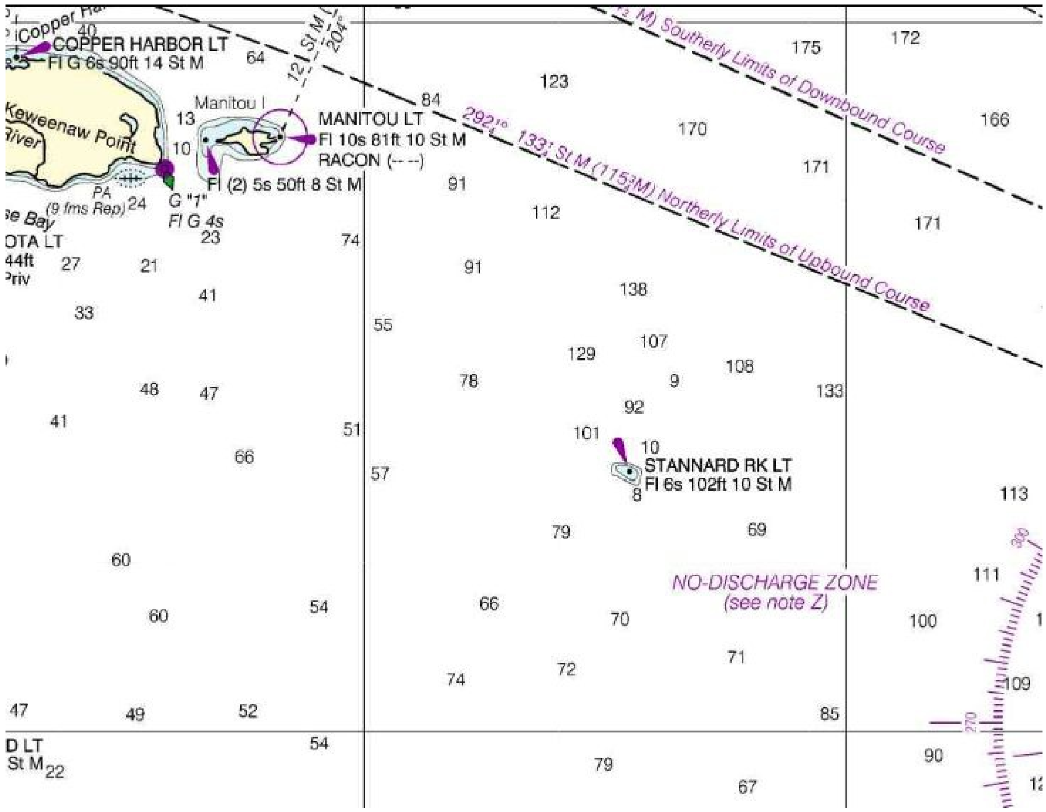


Figure 7. Bathymetric Map of Lake Superior region including Stannard Rock (from 2016 nautical chart; depth in fathoms, except in blue-shaded areas where depth is in feet)

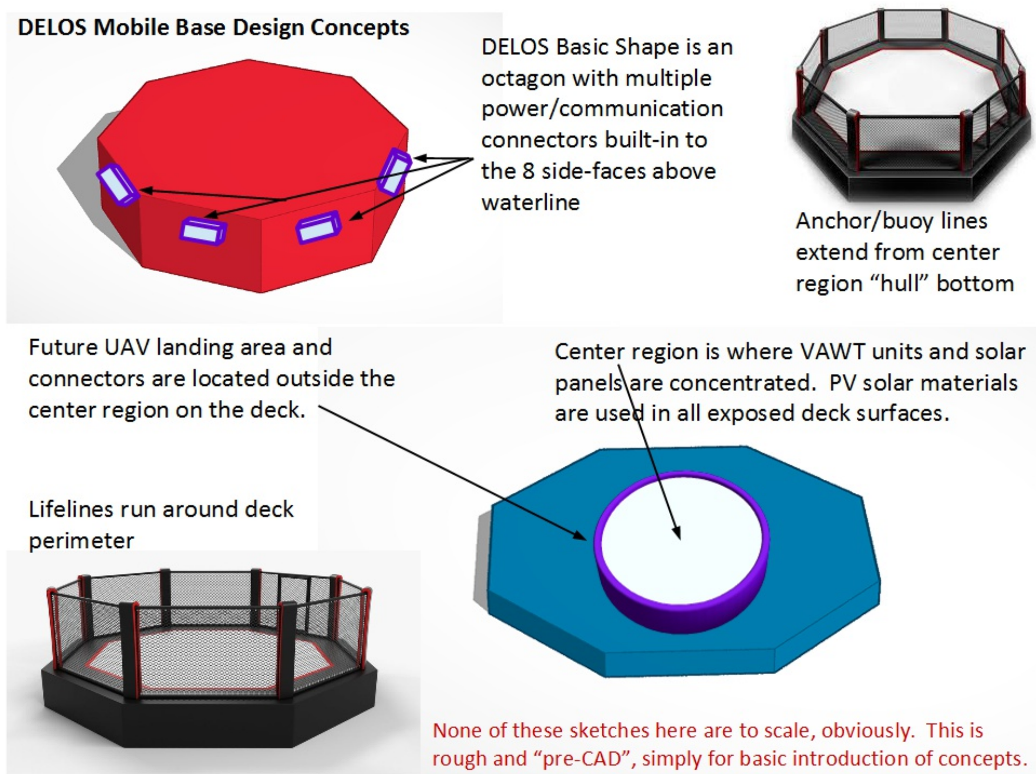


Figure 8. Conceptual View of DELOS Mobile Autonomous Vehicle Base for Engineering and Launching Services ("MABEL")

**A novel design for multi-arm, multi-tool robots that may be used in water and in space**

Unlike certain "shapeshifter" robots proposed for lunar and planetary exploration, this robot is spherical in its "closed" and "sealed" state. Its uniqueness is in how multiple types of appendages can be accommodated, at different times and geometries of operation. There is no top, no bottom, no left, no right. Each of the 12 regular pentagonal panels can spring open as a lid, enabling an arm to extend from within. Each arm can be decidedly different in its design and function, but the common ground is that the arm geometry and mechanics accommodates the internal space allocated for it within the sphere, and other constraints pertaining to extension and also power requirements, etc.

Certain of the 20 regular hexagonal panels serve for rotation and propulsion, as they include small engines (ion thrusters for space, or air/water pressure jets for use in air, water or on land). These provide thrust in one precise direction, perpendicular to the hexagonal panel face. By coordination of activations and firings of different thrusters, the robot is capable of repositioning itself easily and rapidly in any combination of motions to achieve any desired 3D orientation. Once in a desired position, the appropriate arm can be activated and it will emerge from one of the pentagonal panels (as that panel face opens as a lid and enables the arm to extend from the robot interior). Diverse species of arms can interact with the object of study and work, or with other arms of these and other robots. As closed or open units, these spherical robots can interact mechanically with each other, only as spheres or as units with extended arms.

Together with the tetrahedron robot units ("tetrads") - as designed and equipped for ASTRIC operations including tethering (extension and retraction of high tensile strength tethers between the tetrads) – the "futbal" robots operate as units within a variety of simple or complex robot groups and networks. [3, 13, 14]

Figure 9. Not only an inspiration but a practical geometry under construction for both ASTRIC and TETHYS applications

## Impact for and by Space Resources

There are two specific areas of significance and impact regarding existing space resources and those that are planned and particularly those already committed for deployment in coming years. These can be summarized rather simply and concisely.

[1] Improved multi-functional use of what is already deployed in space. Past and current missions have been mostly isolated from one another functionally. This has been the natural "Darwinian" evolution of things. Now this can and needs to change, and while there may be challenges in making existing satellites, rovers, and other

machinery in space become more “utilitarian” for other missions, it is not beyond the range of possibilities. The International Space Station is an excellent example of taking a multi-function approach, and to what extent this model can be applied to other systems either in space already or beyond-change on their mission “drawing boards” remains to be seen.

However, a clear area of multi-functionality is in how the data from various sensor-equipped satellites, especially, is acquired, organized, and distributed. There is enormous capability for instance in using data from both commercial and non-commercial satellites equipped with a variety of sensors, tuned to optical and non-optical (especially IR and near-IR) monitoring of earth locations, both on land and at sea, into being useful for two critical tasks, namely what are the motivations for both ASTRIC and TETHYS Projects in the first place.

One task is the direction of existing space-based sensor capabilities, regarding Earth targets, toward wetlands and general watershed regions, especially the critical interfaces in river mouths and estuaries, coastlines of freshwater bodies, effluents from rivers (especially in high-population urban areas), and areas of coastal flooding and storm flooding, with special attention paid to the combining and mixing of waters and the flora and fauna inhabiting the different now-mixing regions. There can be a utilization of government satellites, including those of military origin and missions. Is not the defense and sustainability of Our Planet the most important defense task that any nation can consider? (The author realizes that this last statement is both rhetorical and opinionated, and also provocatory. It is intended to be a provocation to dialectics!)

The second major task is the observation, sensing, and monitoring of objects in the “other direction” from Earth or whatever are the usual targets to which various satellites and also rovers and ground-based exploration machines are directed. The area of special interest are those asteroids. Earth needs all the “eyes and ears” possible for not only detection of known or rogue threats and objects of interest, but all the variations possible on angles and views, in order to construct effective topological and limnological models of asteroids that may require an ASTRIC type of response. One of the severe challenges for any system like ASTRIC is in being able to plan the precise mission, such as for trajectory modification by one or multiple mechanisms. Success in this domain requires as much reliable knowledge about the precise surface structures and the interior composition of the target asteroids. Moreover, such information can be of inestimable value in planning other missiomns to asteroids, such as for mining $H_2O$ or minerals of value.

[2] The second area of impact for space resources of today and tomorrow, but especially for future space missions, is one over which there is more control since those resources have not yet been deployed and can even be redesigned to some extent. This concerns the <u>vast improvements needed in the design of future space systems in order to share resources</u> especially of power (fuel) and the repair and replacement of components. This translates to: modularity, interchangeability, and common platforms for both hardware and software.

ASTRIC and TETHYS may point out some of these improvement needs, but they are as projects only two broad examples. Others involve such topics as space-based energy production (e.g., solar farms at L5 orbital locations and on the Moon) and manufacturing, plus the obvious domain of human habitation and terraforming of other space bodies for human (and/or robot) colonization.

A vast amount of today's and tomorrow's “space debris” is exactly such – garbage – because there have not been alternative and continued uses for what has been put into orbit or, increasingly, on the surfaces of Moon, other planets, and gradually, asteroids. Design-in of re-use for other active purposes, or re-use of components, is completely reasonable with today's levels of technological competence. It has simply not been in the “thinking equation” for almost all space-targeted systems thus far. Even in the very simplest manner of thinking about the matter, a re-use of any given kilogram of material is a reduction in the extraordinary amount of fuel and launch-spacecraft mass required to move that kilo off planet Earth. But the modularity and reconfiguration that is both possible today and needed urgently is not simply one concerned with masses of material. Vehicles can be designed to be more multi-functional. Spacecraft and instrumentation can learn immensely from the field of software engineering and classic “object-oriented” design thinking. What we design tomorrow can be more like the “Transformers” that began as toys and cartoons. Literally speaking so.

ASTRIC and TETHYS both provide stable platforms for conducting such new design strategies and “engineering symphonies” for the future of how space resources will be configured, positioned, and accumulated in different regions beyond Earth, and the opportunity to put such engineering into practice precisely here on Earth for testing and useful applications in the area of environmental and particularly marine operations is not only unique but mandatory. We can begin to rethink how we deploy and accumulate space resources by experimenting in our lakes and seas, in the Inner Space on which all our continents and all our homes and lifestyles are literally floating islands. In this process we can engineer more efficient and practical systems for Space above, while conducting life-critical missions to achieve balanced sustainable living here on our ever-changing Home Planet.

## Bibliography


[1] Unpublished pre-prints and technical notes prepared by the author, Edward Teller, Yuri Koptov, Vitaly Ginzburg, Carl Sagan and David Finkelstein, initially spanning 1992 - 1995

[2] Dudziak M., Granichin O., Extreme complex systems, uncertain and uncooperative robotic networks, and control strategies based upon stochastic algorithms. In: Proc. of the 28th International scientific-and-technological conference extreme robotics (ER-2017), Nov. 2-3, 2017, St. Petersburg, Russia, 218-230.

[3] Dudziak, M, ASTRIC - Design and control of cooperative robots for rapid deployment in asteroid impact deterrence missions. In: 58th Israel Annual Conference on Aerospace Sciences, Mar. 14-15, 2018 Tel Aviv, Israel.

[4] O. Granichin and N. Amelina, “Simultaneous perturbation stochastic approximation for tracking under unknown but bounded disturbances.” In: IEEE Trans. on Automatic Control, vol. 60, no. 6, pp. 1653–1658, 2015.

[5] O. Granichin, T. Khantuleva, O. Granichina, “Local Voting Protocol for the Adaptation of Airplane’s 'Feathers' in a Turbulence Flow.” In: American Control Conference, May 24–26, 2017, Seattle, USA.

[6] Dudziak, M, ATHOS, a Functional-Logic Operating System for Robot Communities with Self-Organization and Persistent Learning Capabilities. In: Proc. of the 28th International scientific-and-technological conference extreme robotics (ER-2017), November 2-3, 2017, St. Petersburg, Russia, 208-217.

[7] Dashevskiy V., Budkov V., Ronzhin A. Survey of Modular Robots and Developed Embedded Devices for Constructive and Computing Components. In: Ronzhin A., Rigoll G., Meshcheryakov R. (eds) Interactive Collaborative Robotics. ICR 2017. Lecture Notes in Computer Science, vol 10459. Springer

[8] Ivanov, A.A., Shmakov, O.A.: An algorithm for defining the inner geometry of a snakelike manipulator in case of leading link movements along the incremental trajectory. SPIIRAS Proceedings. 49(6), 190-207 (2016)

[9] Calisti,, M, Giorelli, M, Levy, G, Mazzolai, B, Hochner, B, Laschi, C, Dario, P, An octopus-bioinspired solution to movement and manipulation for soft robots, Bioinspiration & biomimetics 6 (3) (2011)

[10] Laschi, C, Robot Octopus Points the Way to Soft Robotics With Eight Wiggly Arms. In: IEEE Spectrum, https://spectrum.ieee.org/robotics/robotics-hardware/robot-octopus-points-the-way-to-soft-robotics-with-eight-wiggly-arms (2016)

[11] M Calisti, A Arienti, F Renda, G Levy, B Hochner, B Mazzolai, P Dario, Design and development of a soft robot with crawling and grasping capabilities. In: Robotics and Automation (ICRA), 2012 IEEE International Conference on Robotics and Automation, 4950-4955 (2012)

[12] C Laschi, B Mazzolai, M Cianchetti, Soft robotics: Technologies and systems pushing the boundaries of robot abilities. In: Science Robotics 1 (1 (2016)

[13] Dudziak, M, ATHOS Multi-Agent Operating Environment for Cooperative and Remote Robotic Networks. In: Int'l Conf. on Control, Decision and Information Technologies , April 10-13, 2018, Thessaloniki, Greece.

[14] Dudziak, M, Multi-Scalar Multi-Agent Control for Optimization of Dynamic Networks Operating in Remote

Environments. In: International Conference in Informatics in Control, Automation and Robotics (ICINCO), July 29-31, 2018, Portu, Portugal
[15] N. Amelina, A. Fradkov, Y. Jiang, and D. Vergados, “Approximate consensus in stochastic networks with application to load balancing,” IEEE Trans. on Information Theory, vol. 61, no. 4, pp. 1739–1752, 2015.
[16] J. Tsitsiklis, D. Bertsekas, and M. Athans, “Distributed asynchronous deterministic and stochastic gradient optimization algorithms,” IEEE Transactions on Automatic Control, vol. 31, no. 9, pp. 803–812, 1986.
[17] A.S. Yushchenko, K.V. Ermishin. Collaborative Mobile Robots – A New Stage of Robotics. In: Proc. Intl. Scientific and Technological Conference EXTREME ROBOTICS. Nov. 24-25, 2016, St. Petersburg, Russia.
[18] M. Chacin, A. Mora, K. Yoshida, “Motion control of multi-limbed robots for asteroid exploration missions.” In: IEEE International Conference on Robotics and Automation, 2009. ICRA '09, Kobe, Japan.
[19] F. Matsuno, Y. Oosako, “Control of an asteroid sample return robot during contact based on complementarity modeling.” In: Procs. of the 40th IEEE Conf. on Decision and Control, 2001, Orlando, FL.
[20] J. Bellerose, A. Girard, D. Scheeres, “Dynamics and Control of Surface Exploration Robots on Asteroids.” In: Optimization & Cooperative Ctrl. Strategies, LNCIS 381, pp. 135–150, Springer-Verlag, 2009.
[21]https://www.esa.int/Our_Activities/Observing_the_Earth/Space_for_our_climate/Satellites_yield_insight_into_not_so_permanent_permafrost – Satellites Yield Insight into not So Permanent Permafrost.
[22] https://www.sciencedirect.com/science/article/pii/S004896971833612X
The influence of global climate change on the environmental fate of anthropogenic pollution released from the permafrost: Part I. Case study of Antarctica/10.1029/2019GL0.
[23] Tollefson, J, Satellite spies methane bubbling up from arctic permafrost. In: Nature, Dec. 14, 2018
https://www.scientificamerican.com/article/satellite-spies-methane-bubbling-up-from-arctic-permafrost/
[24] https://agupubs.onlinelibrary.wiley.com/doi/abs82531
Methane Sources in the Waters of Lake Michigan and Lake Superior as Revealed by Natural Radiocarbon Measurements.
[25] https://www.sciencedaily.com/releases/2018/05/180504082414.htm
Greenhouse gas 'feedback loop' discovered in freshwater lakes.
[26] https://www.lakescientist.com/lake-facts/lakes-climate-change/
Basic Info on different gases and release mechanisms within lakes.
[27] https://eos.org/articles/algae-blooms-and-gas-wells-drive-lake-erie-methane-emissions
Algae Blooms and Gas Wells Drive Lake Erie Methane Emissions.
[28] https://link.springer.com/article/10.1007/s00027-018-0583-2
Dissolved greenhouse gas concentrations in 40 lakes in the Alpine area.
[29] https://oceanexplorer.noaa.gov/explorations/17thunderbay/summaries/phase_3/phase_3.html “Mission Executed”: Using Autonomous Technology to Rapidly Survey Historical Shipwreck Sites.
[30] Meadows G, Brown H, Jenkins L, Shuchman R, BathyBoat: Autonomous Surface Command &Control for Underwater Vehicle Networks.
https://pdfs.semanticscholar.org/a4e6/da2cf62e002ec991d5dadc0b8e01a0db034e.pdf
[31] https://www.michiganradio.org/post/how-autonomous-vessels-could-change-great-lakes-commerce-research How autonomous vessels could change Great Lakes commerce, research.
[32] Wang C, Wei L, Wang Z, Song M, Mahmoudian N, Reinforcement Learning-Based Multi-AUV Adaptive Trajectory Planning for Under-Ice Field Estimation. In: Sensors, 2018 Nov 9; 18(11).
[33] Ziaeefard S, Page B, Pinar A, Mahmoudian N, Effective Turning Motion Control of Internally Actuated Autonomous Underwater Vehicles. In: J. Intell Robot sys (2018) 89:175-1879
[34] https://www.mtu.edu/news/stories/2017/september/researchers-discover-two-historic-shipwrecks-thunder-bay-national-marine-sanctuary.html. Researchers Discover Two Historic Shipwrecks in Thunder Bay National Marine Sanctuary
[35] Brown H, Kim A, Eustice R, An Overview of Autonomous Underwater Vehicle Research and Testbed at PeRL
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.572.7084&rep=rep1&type=pdf