Detailed Project Report for

A Technology Innovation Hub @

Indian Institute of Science, Bangalore

under the

National Mission for Interdisciplinary Cyber-Physical Systems

Executive Summary

The need for Robotics and Autonomous Systems has never been felt more than in the present Covid-19 Pandemic era[1]. The requirement for strict social distancing has led to a lockdown with a complete halt of most economic activities. Even after the lifting of the lockdown, social distancing will necessitate doing more with less people in close physical proximity - which means relying on automation, and in the case of physical processes, it implies the need for Robotics, including telerobotics and collaborative robotics. According to Tractica Research[2], the need to automate physical processes and merge it with the digital ecosystem is going to result in a $248.5 bn market by 2025 comprising Personal robots, Commercial robots, Industrial robots and Military robots.

DST, through its Science and Engineering Research Board (SERB), has awarded a seed grant of INR7.25Cr to IISc to set up a TIH in the technology vertical of Robotics and Autonomous Systems[3]. The TIH will be set up as a Section 8, not for profit company, as mandated by DST and will be tentatively named as the "i-Hub for Autonomous Intelligence and Robotics Foundation" and will be called ARTPARK in the rest of the report.

The primary goal of this ARTPARK will be to provide a platform to translate innovative technology research into POC (Proof of Concept), Productization and finally Commercial Application. The hub will also build an ecosystem of venture studios, Venture Funds and other capital providers so that these technologies can be spun off as companies after achieving TRL 5-6 stage. Some potential grand challenge problems in Avatar Robotics, Drone Skyways and some Strategic applications will be explored.

ARTPARK will also work on some projects which may not have high commercial applicability but have high social good associated with them. Every project will undergo a thorough Cost Benefit Analysis and Risk Analysis with pre-defined Quantitative goals.

The ARTPARK will also aim to develop a pool of skilled global level manpower who have not only theoretical knowledge but also practical skills in the area of AI, Robotics and Autonomous Systems. National and International collaborations with reputed Academic Institutes and Private Companies will be an important goal for ARTPARK as the objective is to produce technology which meets the objectives of social good and/ or commercial applicability on a global scale.

The overarching remit of the ARTPARK is to work in the area of AI, Robotics and Autonomous Systems. This has wide applicability in many different fields including Mobility, Drones, Urban Transportation, Agricultural, Healthcare, Education, Water Sufficiency, Energy Footprint, Supply Chain Optimization, Smart Cities, Manufacturing, Governance etc. ARTPARK will work in a few of these areas and other such areas with social and commercial applicability with possibilities for widest possible impact.

Today's world is one driven by technology. Large technology companies have market caps which are larger than many nations' GDP and profits which exceed the tax collection of entire countries. In such a world it is critical for India to have technology sovereignty in as many areas as possible. ARTPARK aims to contribute towards making such global technology behemoths out of India.

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[1] https://www.therobotreport.com/march-2020-robotics-investments-recap/

[2] Robotics market forecasts : https://tractica.omdia.com/research/robotics-market-forecasts/

[3] Letter No DST/NM-ICPS/MGB/2018, dated March 03 2020.

CERTIFICATE

Name of the TIH: **Technology Vertical:**

1. This is to certify that the Detailed Project Report (DPR) on the Technology Vertical Robotics and Autonomous Systems is prepared and submitted to Mission Office, NM-ICPS, DST is as part of implementation of Technology Innovation Hub (TIH) at . IISc, Bangalore under National Mission on Interdisciplinary Cyber-Physical System (NM-ICPS).

2. This is to certify that this DPR has been checked for plagiarism and the contents are original and not copied/taken from any one or from any other sources. If some content was taken from certain sources, it is duly acknowledged and referenced accordingly.

3. The DPR will be implemented as per the Terms, Reference and Clauses stated in Tripartite Agreement signed on 14 December 2020 between Mission Office, DST, IISc, Bangalore and I-Hub for Robotics and Autonomous Systems Innovation Foundation

Date: September 15 2021

Place: IISc Bangalore

Bharadwaj Amrutur BBharadwaj

Name(s) and Signature(s) of Project Director (s)

Endorsement from the Head of the Institution

1. Certified that the Institute welcomes participation of . Prof Bharadwaj Amrutur as the Project Director(s)/Co- Principal Director for the Technology Innovation Hub (TIH) and that in the unforeseen event of discontinuance by the Project Director, the IISc will identify and place a suitable faculty as Project Director for fruitful completion of the TIH activities.

2. Certified that the Host Institute shall provide basic facilities, faculty support and such other administrative facilities as per Terms and Conditions of the award of TIH, will be extended to TIH.

3. As per Tri-partite Agreement, the Host Institute (HI) shall play its role and fulfill its responsibilities for the success of TIH.

Date: 16.09.2021
Place IISc Bangalore

Name and signature of Head of Institution

कप्तान श्रीधर वारियर (सेवानिवृत्त)
Capt. Sridhar Warrier (Retd.)
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1. Context/Background

The Department of Science & Technology (DST) has identified the interdisciplinary area of Cyber-Physical Systems (CPS) as an "*emerging field, progress in which is expected to have significant impact on health care, urban transportation, water distribution, energy, urban air quality, manufacturing and governance*"[4]. Towards this end, it has set up a National Mission on Interdisciplinary Cyber Physical Systems (NM-ICPS), which will further this ambitious vision. A critical strategic component of this mission, are the Technology Innovation Hubs (TIH), that have been setup in various academic institutions, each focusing on a technology vertical, and that are expected to further the goals of the mission by undertaking:

(a) Technology Development: Through expert-driven research, Consortium based Research through Cluster-Based Network Programmes, directed research for the specific requirements of Industry, other Govt. verticals and International Collaborative Research Programmes

(b) HRD & Skill Development: Through Fellowship Based UG/ PG, Ph.D., Post- Doctoral and Short Term Training for Faculty

(c) Innovation, Entrepreneurship and Start-up Ecosystem: To enhance competencies, capacity building and training to nurture innovation and Start-up ecosystem.

(d) International Collaborations: To establish and strengthen the international collaborative research/ Technology Development.

DST, through its Science and Engineering Research Board (SERB), has awarded a seed grant of INR7.25Cr to IISc to set up a TIH in the technology vertical of Robotics and Autonomous Systems[5]. The TIH will be set up as a Section 8, not for profit company, as mandated by DST and will be tentatively named as the "i-Hub for Autonomous Intelligence and Robotics Foundation" and will be called ARTPARK in the rest of the report.

We broadly classify the objectives of ARTPARK into two, inter-related aspirations:

a) Technology goals, and

b) Translation goals.

In this Detailed Project Report, we outline our vision and detailed strategic and operational plan for our hub over the next 5 year period to meet these twin aspirations.

The need for Robotics and Autonomous Systems has never been felt more than in the present Covid-19 Pandemic era[6]. The requirement for strict social distancing has led to a lockdown with a complete halt of most economic activities. Even after the lifting of the lockdown, social distancing will necessitate doing more with less people in close physical proximity - which means relying on automation, and in the case of physical processes, it implies the need for Robotics, including telerobotics and collaborative robotics. Further given the critical call by the government to create technology sovereignty in critical areas, the ability to create technology, influence & own standards and create globally competitive companies in the area of Robotics and autonomous systems, become critical, not only from economic reasons, but also from strategic reasons.

Over the last half a century, we have succeeded very well in achieving automation of information and digital processes. IDC research suggests that the amount of the newly created data in 2025 was predicted to grow to 175 zettabytes (175 trillion gigabytes)[7]. Post Covid world, it is going to accelerate massively, considering that more and more activity will be online and remote. The amount of data about digital processes is allowing us the critical foothold to advance to the next step which is automating

[4] Detailed Project Report for the National Mission on Interdisciplinary Cyber Physical Systems, Department of Science and Technology, Govt. of India, dated 31-05-2018.

[5] Letter No DST/NM-ICPS/MGB/2018, dated March 03 2020.

[6] https://www.therobotreport.com/march-2020-robotics-investments-recap/

[7] https://www.seagate.com/files/www-content/our-story/trends/files/idc-seagate-dataage-whitepaper.pdf

physical processes and fusing it with digital interactions, and it involves developing solutions along three main axes:

a) Mobility: involving motion of machines in structured, semi structured and unstructured environments, safely and efficiently,
b) Interaction: involving physical interaction of machines with its surrounding environment, and
c) Management: Ability to manage remote actions intelligently and cohesively with human workflows.

According to Tractica Research[8], the need to automate physical processes and merge it with the digital ecosystem is going to result in a $248.5 bn market by 2025 comprising Personal robots, Commercial robots, Industrial robots and Military robots.

1. The personal segment—robots used for entertainment, cleaning, education, security, and household applications.
2. The commercial segment—robots used for transportation (cars, UAVs and others), medical and surgical purposes, agriculture, and construction, among other applications.
3. The industrial segment—robots used in applications such as welding, assembly, painting, and material handling. This segment is going to see a massive growth post covid.
4. The military segment—for unmanned aerial, ground, military exoskeletons, and underwater vehicles, among other applications.

Autonomous/Semi-Autonomous mobility of vehicles in warehouses, mines, ports, campuses etc. has the potential of tremendous economic impact. These spaces are unstructured, yet restricted in terms of overall traffic and hence offer a possibility of development of robust solutions based on latest advances in Sensors and AI. In addition, air mobility of micro and mini-air vehicles opens up new societal and business applications, while it has its own different set of technological and regulatory challenges.

Interaction involves machines manipulating their environment - e.g. harvesting or deweeding in agriculture, picking and placing of objects in warehouses, co-working with a factory worker to provide tools and other support etc. Creating technologies that are safe and allow for creating a diverse set of interactions needing various degrees of skilling, is a key research challenge.

Another perspective for robots comes from thinking about their physical dimensions. This can range from mega (electronically controlled tractors, trucks, cranes), to macro (AGVs, electronically controlled forklifts), to human (service robots, electronically controlled wheelchairs, Assistive Devices), mini (household robots, MAVs) and finally to micro scale (microbots). The solution approaches to mobility and interaction will be fundamentally different for micro-bots, compared to that at other scales. Micro bots offer promising applications in healthcare, especially for surgery, targeted drug delivery etc.

Achieving cyber-physical autonomy for these machines in a safe, secure & reliable manner is the key scientific and engineering challenge, and the main intellectual and technological focus of our hub. The scientific and engineering foundations for these technologies are in Controls, Optimization, Machine Learning & AI, Embedded and Real-time Systems, Statistical Signal Processing, Software Engineering, Electronics, and Sensors & Actuators, user interface technologies like AR/VR. Successful development of technologies in this domain, requires a truly interdisciplinary and collaborative approach, cutting across these diverse areas, backed by world class experimental facilities. IISc has deep strengths in all of the above areas and will provide the technological pillar for this hub. More details on some of the proposed foundational research and technology developments, follow later in this report.

One of the major roles of the TIH, as envisioned by DST, is to enable the translation of innovative research and technologies into the marketplace. In order to provide the needed flexibility to achieve this important aspiration, the TIH is being set up as a not-for-profit company, wholly owned by IISc, but which will operate by the rules of the Ministry of Corporate Affairs, independent of IISc. However the TIH will work closely with researchers from IISc via funding support of students, faculty, facilities and academic exchanges.

[8] Robotics market forecasts : https://tractica.omdia.com/research/robotics-market-forecasts/

While there are many startup incubators already present in the country, these focus on supporting and mentoring startups to develop a viable business, once their key underpinning technologies have already been de-risked. However, there is currently no institutional framework, to bridge the gap between the academic research output and the technology de-risked startup phase. There are a few institutions and programs around the world, focusing on this aspect like SRI[9], MILA,[10] MIT Media labs[11] etc., which attempt to bridge the gap of research and productization. IISc's TIH will attempt to play a similar role, to nurture the creation of innovative technologies based on deep research that address important societal needs and that can be delivered to society via economically sustainable mechanisms. More details on our approach to this translation problem are detailed subsequently.

[9] https://www.sri.com
[10] https://mila.quebec/en/
[11] https://www.media.mit.edu/

2. Problems to be addressed

There are significant opportunities, and challenges in automating physical processes in unstructured environments, especially those involving mobility (e.g. to move things/people) and interaction (e.g. cooking, co-working)[12]. Robots have always found applications in high end manufacturing plants like in automotive factories[13] (see for example the Toyota Factory). They have found limited success in home uses (see for example roomba[14]). However with latest advances in ML & AI, spurred further by the COVID Pandemic[15], we anticipate an acceleration in their adoption at work and home.. This figure from the robot report.com website shows the spread of Robotics related businesses in ASIA and EUROPE.

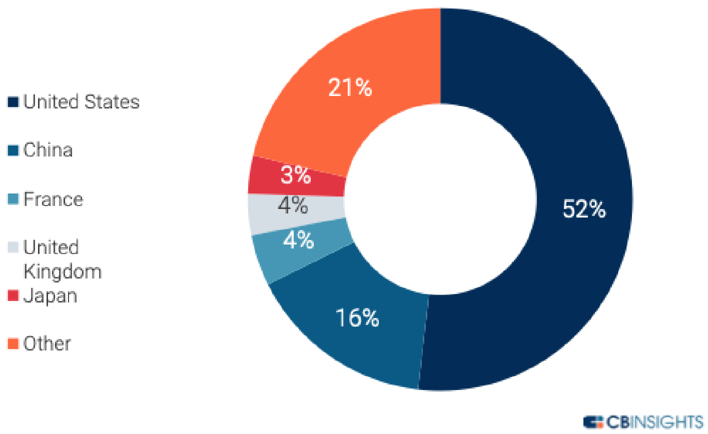
(Image from www.therobotreport.com)

Further from the technology research and translational roadmap perspective, we are looking at,

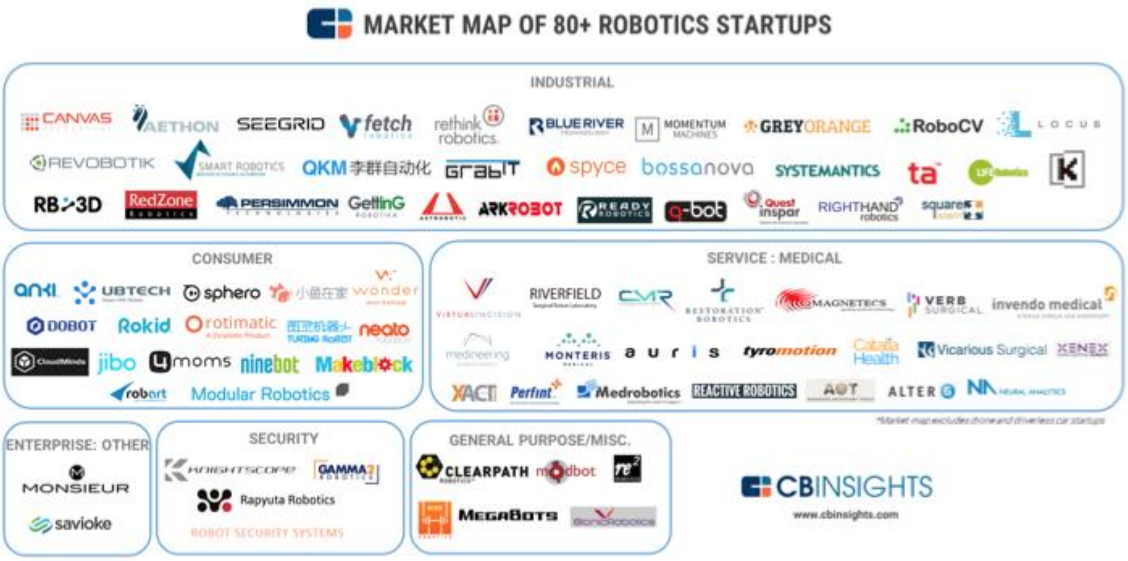
a. Teleoperation of robots (1-3 years) - By combining high speed and low latency communication (5G), we can enable robots to address the uncertainty in the environment by allowing human perspective and ability to monitor and manage the robot operation. The problems being addressed can range from tele presence to tele collaboration.
b. Teleoperation combined with limited autonomy (2-5 years) - By combining low latency communication with limited autonomy quite a few tasks in consumer and commercial segments can be automated. Specially for a country like India, it will be a boon for enabling employment for people without the need for migrating to richer countries.
c. Fully autonomous robots (5-9years) - By leveraging full autonomy, we can enable complex social workflows and enriched behaviours. This can find deeper adoption in multiple markets from personal, commercial and military markets.

We also need to build an enabling environment and ecosystem to convert the research into translational output as the number of robotics companies in India is still small - so our TIH is being set up at the right time to give a boost to this nascent industry. Globally we are seeing a lot of research and development activity, led by the US and followed by China in the number of investments deals.

[12] https://www.therobotreport.com/robotics-investments-recap-may-2019/
[13] https://www.robots.com/articles/how-toyota-uses-automation-to-improve-processes
[14] https://www.irobot.com/roomba
[15] https://www.therobotreport.com/survey-finds-coronavirus-changing-consumer-comfort-ai-robots-self-driving-cars/



Given the critical nature of the technology and its strategic place in altering the economic advantage for the nation, we need to create a large talent pool of researchers and translational output in the form of startups. Except GreyOrange and Systemantics, we see no other major Indian startup in top 80 startups globally.



To achieve success at the global level, we plan to address these five problems:

a) Facilities

Access to world class laboratories and testbeds is a must[16], if we hope to develop workable and robust solutions. We plan to setup such facilities in IISc at three scales:

(i) Indoor Robotics Lab called the Makery. This will have many off-the-shelf robots as well as maker space to build, measure, explore and study various solutions.

(ii) Small outdoor testbed: This will be set up in IISc's main campus and will have facilities for testing drones in indoor spaces under various conditions and a small test track for testing autonomous and tele-operated vehicles in indoor-like environments.

(iii) Large outdoor testbed: This will be set up in IISc's Challekere campus and will provide much more extensive facilities for testing outdoor robotic systems.

[16] See for example: https://mcity.umich.edu/our-work/mcity-test-facility/#

(iv) A data testbed which will allow privacy preserving collection, sharing and analytics of data to drive AI/ML research for robotics, autonomous systems and their various applications in mobility, smart cities etc.

b) Funding

Besides the seed funding from DST, we will raise additional funding from other governmental and private sources, to build world-class facilities as well as support high end technology research in this domain

c) Talent

This area needs both technology talent from diverse backgrounds (electronics, computer Science, Mechanical), both young and experienced, as well as entrepreneurial talent to help spin out the developed technologies. This talent should operate at the global standards. The hub will foster the creation and training of such talent.

d) Training

As this industry matures in India and outside, we need to educate more of our youth in these domains. In addition, existing labour, used to doing things in a traditional way, will also need to be retrained[17]. In addition to technological skills, the hub will also look to impart technopreneurial skills via some new innovative programs.

e) Innovations

Achieving cyber-physical autonomy for robotic systems, in a safe, secure & reliable manner is the key scientific and engineering challenge, and the main intellectual focus of our proposal. This will lead to development of many innovative technologies, that will provide the necessary fuel to create deep-tech startups in this space.

We will next give a brief overview and motivation for the initial set of technology challenges we plan to address via several exploratory missions. More details on these are available in the appendices.

- Moving people and goods is the lifeline for any economy. There is a great interest to explore using the immediate airspace, above any city[18] to support short-haul air traffic. Such a network has to necessarily rely on automation and we are proposing an exploratory mission to find solutions to create, manage and deploy future urban air transportation networks.
- The last mile problem[19] is a major challenge for ground mobility. While, automating mobility on public Indian roads will remain a distant dream, a prudent first step will be to tackle such automation in more restricted, yet unstructured and uncertain environments like campuses, warehouses, docks etc*.* which will be our second major mission*.* This will go a long way in addressing the last mile problem in these, economically vital settings.
- The twin pillars of manipulation and interaction require robots to interact with the physical and social world[20]. Endowing them with these capabilities, especially to work in unstructured and uncertain environments, with natural ease and ability to collaborate with humans, will greatly enhance their value and utility in multiplying our productivity, efficiency and reach. This will be our third major exploratory mission.
- Advances in micro- and nanotechnologies have enabled robotic manipulation from sub-mm to molecular length scales[21]. These micro- and nanobots can have multiple functionalities, can be maneuvered and positioned with a high level of control and thereby

[17] See for example courses for retraining workers in manufacturing by http://ekyami.com/
[18] https://utm.arc.nasa.gov/index.shtml
[19] https://en.wikipedia.org/wiki/Last_mile_(transportation)
[20] See for example: https://www.frontiersin.org/articles/10.3389/frobt.2016.00058
[21] https://en.wikipedia.org/wiki/Nanorobotics

make deep impact in future biomedical and cyborg applications. Enabling this capability is our fourth exploratory major mission project.

- Achieving these challenging mission mode goals will require a confluence of foundational technologies in Machine Learning & Control, Advanced Communication & Computing, Motor & sensor technologies, modeling and simulation, and user interface technologies, involving a judicious combination of theory and practice. These require a truly interdisciplinary and collaborative approach, cutting across many different areas and complementary entities backed by world class experimental facilities[22].

Finally, data is the critical fuel for all future AI and ML related activities, with Robotics and Autonomous Systems being no exception. We will set up an open source, privacy preserving, data collection and exchange testbed, not only to aid research in robotics and autonomous systems, but also for other areas like drug discovery, smart cities, etc. This activity will allow us to develop technologies in emerging topics like data fiduciaries, confidential computing, distributed learning etc. As a spin-off, we will create certain strategic open data sets for helping advance ML/AI approaches in Robotics as well as Navigation.

There is a significant gap between academic engineering research and its translation to products and solutions[23]. This can be tracked to two problems: the upstream gap and the downstream gap. Upstream gap refers to identifying problems that could have a high impact potential in terms of translation into products. The downstream gap refers to the moving solutions from academia into industry. With many programs in startup incubation and innovation, started by both government, and industry, we seem to have a good handle for addressing this latter gap. However the upstream gap still remains and it is left to faculty to somehow identify the relevant problems for research. Our proposed TIH will address this gap by curating problems statements with inputs from a diverse set of stakeholders, so that the chances of doing relevant research increases manifold.

[22] See for example the test field: https://www.stofficetokyo.ch/japan/technology/fukushima-robot-test-field
[23] https://www.thestatesman.com/opinion/relevance-of-research-1502790206.html

3. Aims and Objectives

DST has clearly spelt out the aims and objectives as part of the NM-ICPS detailed project report. We reproduce it here in the form of a table, with quantifiable goals to target.

S.No.	Target Area	1st Yr	2nd Yr	3rd Yr	4th Yr	5th Yr	Total
1	Technology Development						
(a)	No of Technologies (IP, Licensing, Patents etc etc)	5	11	20	20	20	76
(b)	Technology Products	3	5	10	10	10	38
(c)	Publications, IPR and other Intellectual activities	25	50	75	75	91	316
(d)	CPS Research Base	10	40	50	75	75	250
2	**Entrepreneurhip Debelopment**						
(a)	CPS-GCC - Grand Challenges and Competitions	1	1	1	1	1	5
(b)	CPS-Promotion and Acceleration of Young and 1 Aspiring technology entrepreneurs (CPS-PRAYAS)	1					1
(c)	CPS-Entrepreneur In Residence (CPS-EIR)	2	3	8	10	10	33
(d)	CPS-Start-ups & Spin-off companies	4	6	14	14	14	52
(e)	CPS-Technology Business Incubator (TBI)	1					1
(f)	CPS-Dedicated Innovation Accelerator (CPS-DIAL)	1					1
(g)	CPS-Seed Support System (CPS-SSS)	1					1
(h)	Job Creation	100	1400	4000	4000	4000	13500
3	**Human Resource Development**						
(a)	Skill Development	170	190	200	220	240	1020
(b)	Graduate Fellowships	15	25	100	100	100	340
(c)	Post-Graduation Fellowships	5	17	20	20	0	62
(d)	Doctoral Fellowships	2	15	8	0	0	25
(e)	Faculty Fellowships	0	3	3	0	0	6
(f)	Chair Professor	0	3	3	0	0	6
4	International Collaboration	2	2	2	2	2	10

Table 1: Aims and Objectives of the TIH with some quantifiable targets

4. Strategy

4.1. Structure and Vision

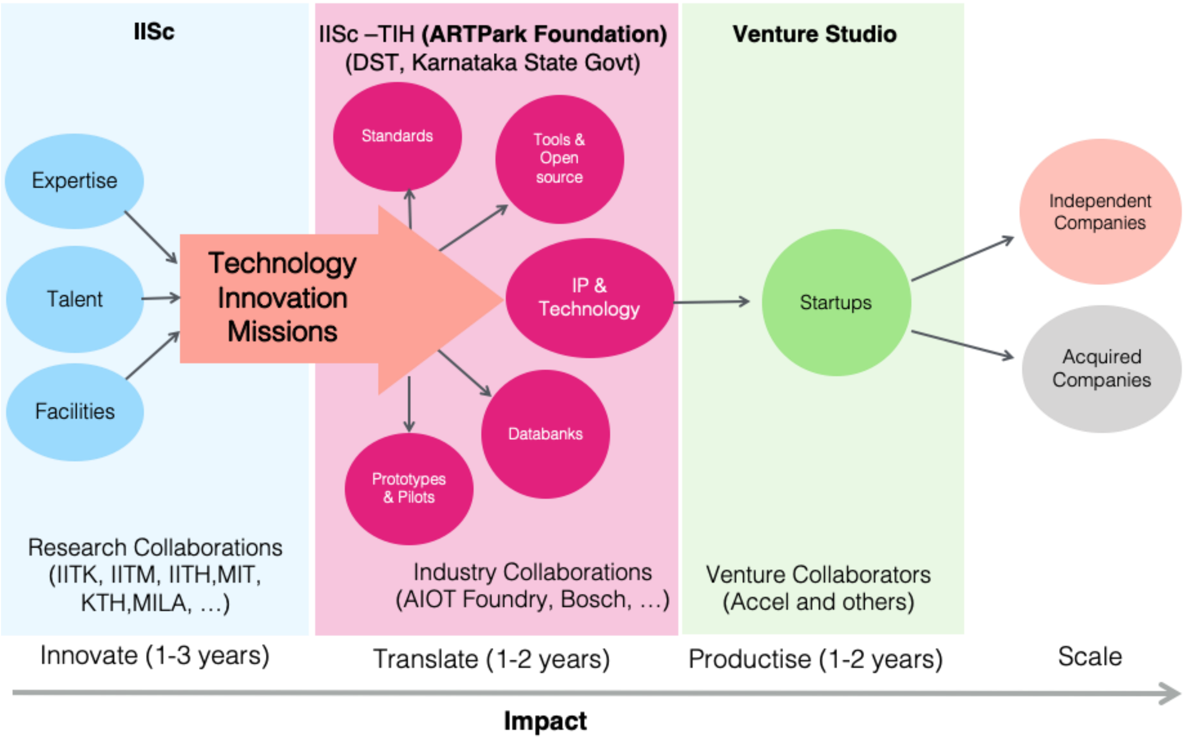


Figure 1: The Hub will act as a bridge between academic research and startups.

IISc's TIH will be an independent Section-8 (Not For Profit) company, wholly owned by IISc. It will be seeded by DST's ICPS grant, and will secure funding from the Karnataka State Govt as well as other non-governmental sources. It will catalyze "Translational Technology Innovation" by carefully identifying promising, large impact opportunities, and shepherding this creation process via focused Technology Innovation Mission Projects (Figure 1). The projects will build upon foundational research carried out at IISc and collaborating academic institutions both in India and globally, leading to creation of IPs and Technology Artefacts, that will then be licensed into startups. The startups will be incubated outside the hub, in incubators or a venture studio, connected with TIH. Other outputs of the technology missions will be: contributions to national and international standards regulations and guidelines, open source software and tools, open databanks, and prototypes & pilots.

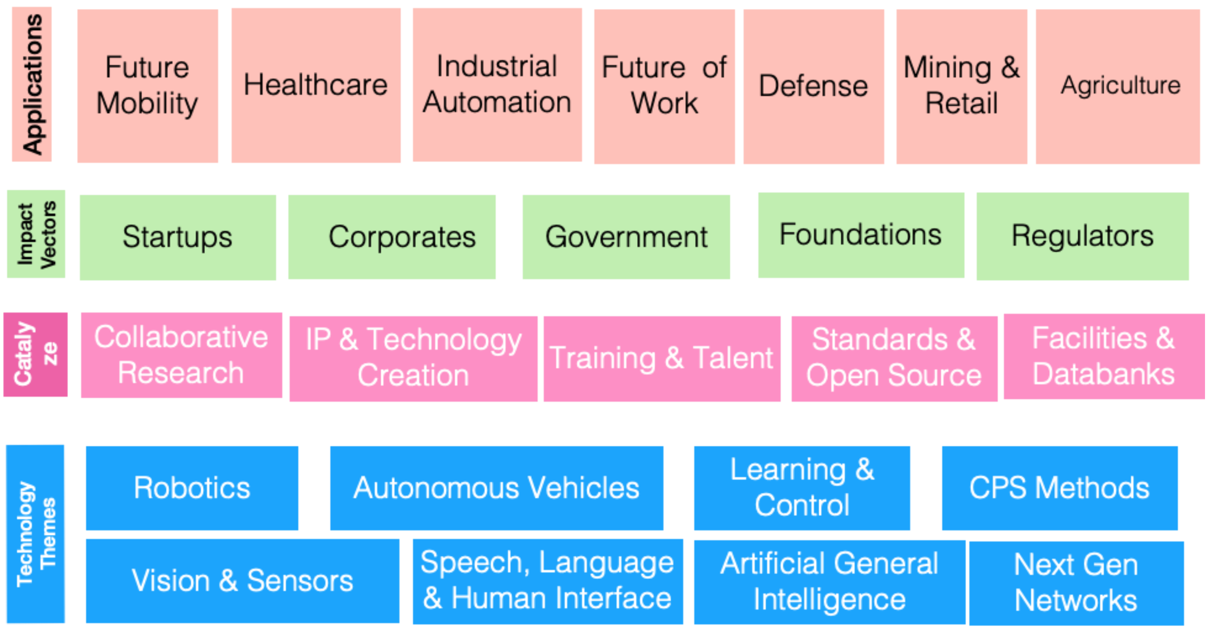


Figure 2: Innovation to Impact Stack

From an operational perspective, the TIH will catalyze high impact technology mission projects built upon foundational technology themes like Robotics, Autonomous Vehicles,and others via funding collaborative mission mode Technology Innovation Projects, that are targeting specific application verticals ranging from Future Mobility, to Agriculture (see Figure 2). The impact in these verticals will be achieved via startups, licensing to existing corporates & foundations and influencing standards and regulations. We will next give a brief of the key components in each of the layers of the Innovation to Impact Stack.

4.1.1. Technology Themes

Robotics provides great opportunities for innovations in component designs, Software, Electronics, Algorithms and finally Manufacturing. High quality but low cost motor design, their controllers, embedded real-time OS and middleware, formal techniques, low cost sensors for localization, perception, real-time multi-sensor fusion, secure hardware and software are some of the key areas, ripe for innovation. Tele or Supervised Robotics will be a crucial technology that will play an immense role in the future. These are already available in specialized domains like surgery[24]. But making these technologies low cost, versatile, and robust will enable mass deployment and open up new services industry for remote delivery of all kinds of skills and not just surgical skills.

Autonomous vehicles for land (both indoors and outdoors) and air (micro and medium sized) offer opportunities in innovation and manufacturing. Technologies for low cost sensors, infrastructure needed to support operations, tele operation and management, optimal utilization of next gen wireless, novel operation modes like platooning, swarming, exploration, etc. are some of the areas ripe for further innovation.

Learning and Control is a hot topic of research and innovation to enable these machines to work in complex unstructured and semi-structured environments. Complexities of the machine and its interactions with the environment - preclude classical approaches of control and need to use data driven approaches based on ML and AI. However engineering these approaches to be reliable and explainable, as well as incorporation of domain knowledge, is an exciting challenge.

[24] https://www.intuitive.com/en-us

CPS Methods involving co-design and co-simulation of hybrid systems (digital-cyber portions along with the analog real-world environments), will be critical to successfully engineer these next generation robots, and will need innovations in new analysis, verification and testing techniques.

Vision and Sensors, both the hardware and the algorithms will be critical differentiators and enablers for these machines. From the hardware perspective, motors, mems, fibre optics, flexible sensors, micro-sensors, mm-wave, lidars, video and stereo, array microphones, etc. are some of the important technologies which offer interesting opportunities for innovation.

Speech, Language and Human Interface will be essential to be able allow a larger number of the general population to interact, use and work with these robots. Speech and Language especially is the most important and promising as it can lead to a very natural and low cost way for humans to interact with these machines. At the same time other modalities of Human-Machine Interfaces will also become extremely important areas to focus on.

Artificial General Intelligence where the robot is able to work and handle situations it has not been trained for, will become an essential requirement as they start getting deployed in ever more unstructured and uncontrolled settings. Being able to design behaviours where these machines can do "reasonable" things (i.e., simulating "common sense") in unusual situations, will become a critical engineering requirement (analogous to exception handling in software design).

Next Gen Networks involving high bandwidth uploads and low latency reliable communications will provide a different paradigm for designing connected robots - where data, information and inference can be shared across heterogeneous machines in real-time to improve their operations. Hence we will no longer think of designing isolated machines - but connected machines which offers exciting and challenging opportunities for innovation in all aspects of their engineering.

4.1.2. Catalysis

Collaborative Research drawing upon expertise from a diverse set of individuals and organizations will be essential to achieve speed, scale and impact. However, to facilitate this, the right frameworks and incentives will need to be created and managed and will be one of the key roles for the hub.

IP & Technology Creation is another key focus area of the hub. IP identification, protection and management will be critical to ensure a good value proposition for the underlying technologies and will also enable the resultant activities to achieve global reach.

Training & Talent creation is a critical requirement, in order to feed and sustain these next generation industries. The hub will work closely with IISc and other institutional partners to create cutting edge courses for training of manpower at all levels.

Standards and Open Source will be critical to create an inclusive ecosystem within India that will provide a level playing field in terms of opportunities to many innovators, who otherwise might not have the deep pockets to enter these new areas. The hub will strive to drive these two aspects as a key mission goal.

Facilities and Databanks are essential to develop and test new technologies in these domains. Good facilities for robot and vehicle testing and curated databanks to develop AI/ML algorithms to operate these, will be critical pieces that the hub will facilitate.

4.1.3. Impact Vectors

Startups

This will be one of the key measurable outputs for the TIH. The hub will work closely with (one or more) venture studios/startup incubators to create an early connection to ongoing technology developments, so that a good synergy and direction to the research is established early on. This will be done via sourcing entrepreneurs-in-residence from the venture studios. Clear NDAs and IP licensing agreements will be established between the TIH and the venture studios to facilitate easy and frictionless translation.

Corporates

CSR support from corporates will be sought for funding projects/facilities that will lead to public good. In addition, partnerships with corporates for designing and building specific technology components will be sought, to allow rapid creation and delivery of application solutions. Clear NDA and IP sharing agreements will be set up.

Government

Specific Govt. ministries and their organizations like Meity/{CDAC, NIC}, DOT/CDOT, MoHUA/SCM, MoD/DRDO, DST/CSIR will be taken on board as partners for specific mission projects. Additionally, regulatory and standardization bodies like BIS, TSDSI, TEC, ARAI, DGCA will be involved at various stages of the mission projects, to ensure that effective contributions to policy and standards can be made.

Foundations

Ekstep foundation, Bill & Melinda gates foundation, Omidyar, Premji Foundation etc foundations will be involved for projects that involve social good.

Regulators

ARAI, DGCA will be two key regulatory agencies, with whom we will establish close relationships so that our research and facilities can be useful to them as they form new regulations and policies.

5. Application Areas

Digital and IT automation has helped cut down costs across industries. AI is now augmenting machines with low level intelligence capabilities, that allow them to take over routine and mundane tasks from humans. This ongoing dynamic of replacing human labor by machines for low-cognitive tasks, is only going to accelerate, thanks to the ongoing Covid pandemic. The pandemic has brought to a standstill all industries that rely on humans working in close physical proximity. Hence, automation and robotics technologies that allow humans to contribute from safe distances, will emerge and proliferate. While in the short term this may disrupt the labor market, it will be our responsibility to retrain workers to acquire new skills and take up higher-end jobs requiring mastery of using robots as (very sophisticated) tools and cohesive workflow involving the use of unique abilities of human beings with robots.

Future Mobility

We can examine mobility along multiple dimensions:

a) Loads: Goods or Humans
b) Environment: Open, Restricted or Closed
c) Space: Land, Air or Water

While there is a lot of excitement about autonomous cars in the west, autonomous mobility has already reached commercial deployments in restricted environments like warehouses to move goods[25]. With falling costs of radar, lidar and cameras, and advances in algorithms for mapping navigation, and path planning, we anticipate the adoption of these technologies across a wide spectrum of industries - in manufacturing, agriculture, last-mile transport, mining, etc. Parallel advances in 5G will provide additional technological tools to facilitate robust and failsafe deployments.

Air vehicles, especially for logistics and surveillance, is poised to grow rapidly, once appropriate regulations are in place[26]. This market is expected to grow to USD 29 Billion by 2027[27] and hence offers enormous opportunities for Indian companies. Our hub's focus on creating testbeds as well as

[25] https://www.aboutamazon.com/amazon-fulfillment/our-innovation/what-robots-do-and-dont-do-at-amazon-fulfillment-centers/
[26] https://www.pymnts.com/news/regulation/2020/faa-to-propose-safety-standards-for-delivery-drones/
[27] https://www.marketsandmarkets.com/Market-Reports/drone-logistic-transportation-market-132496700.html?gclid=Cj0KCQjwnv71BRCOARIsAIkxW9GzuKI8169oVZeY2CiVwUnK6iB2-Y6bm1FCQ4VHYXVYfWzNEi9YWMEaAmqwEALw_wcB

technologies for managing airspace, will be crucial to inform our regulators as well as provide inputs for standards in this space.

Autonomous boats (some calling it “roboats”) could be interesting to track as they are key to industries such as shipping and mining, with much smaller autonomous boats replacing large ships, with minimal or no crew. These could potentially reshape the entire industry. In fact, some reports suggest that autonomous boats might become a reality faster than autonomous driving[28].

Healthcare

Healthcare is going to change in a big way, with innovations in drug discovery, drug delivery to diagnostics to telemedicine and robotic surgery. Three things are driving this change:

a. Robustness of AI in going through large amounts of data and turning up combinations, specially useful in drug discovery.
b. Low doctor to patient ratio (1:1700) in countries like India, making accessibility of scarce healthcare resources important
c. A push towards more affordable healthcare system

Telemedicine is poised to accelerate post-COVID. Teleoperated robotic systems offer additional, physical modes of interaction with patients, which are missing from current telemedicine systems. The current systems are restricted to audio and video interactions and are good for consultations. However in the future, a robotic nurse can interact with patients, at the behest of the remote doctor, and take vitals measurements that involve putting a stethoscope, cuffs for BP, place US probes, help patients to sit/walk, etc. The relevance and need for such technologies has never been felt more than in the current pandemic. While robotics-assisted surgery is well established now, the ability to harness micro-robots for healthcare applications will open up new capabilities and opportunities[29].

Industrial Automation

Traditional industrial robotics has found space in large manufacturing houses - especially in the automotive sectors. However the emerging collaborative robotics market will benefit SMEs and is expected to grow at CAGR of 41% over the next 6 years to be USD 8 billion[30]. This report states that *“Unlike traditional industrial robots, collaborative robots (cobots) provide a fast ROI (as low as 6 months in many cases), which benefit both SMEs and large companies. This is one of the primary drivers for its adoption. In tandem, emerging companies offering low-cost cobots and their increasing affordability is leading to a greater adoption among various industries.”* Some of the technology themes that will be addressed by our TIH in the areas of safety critical control, data driven control etc., will help provide key IPs for these applications.

Future of Work

Future of work is a critical part of our changing economic landscape. As we discussed in the introduction to this section, the labor market will undergo a major churn post Covid. Ironically, human labor will become more valuable[31]. However, existing labor will have to be retrained to adapt to this changing world and especially in industrial applications, be trained to use more sophisticated robotic tools. Tele-robotics will also enable emergence of new service industries, which can provide remote physical solutions in healthcare, agriculture, mining, customer care, transportation and a whole slew of other industry verticals[32].

With automation, three critical changes are expected,

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[28] https://emerj.com/ai-adoption-timelines/autonomous-ships-timeline/

[29] Inner Workings: Medical microrobots have potential in surgery, therapy, imaging, and diagnostics, PNAS Nov. 2017, https://www.pnas.org/content/114/47/12356

[30] https://www.marketsandmarkets.com/Market-Reports/collaborative-robot-market-194541294.html?gclid=Cj0KCQjwnv71BRCOARIsAIkxW9E3bfMwLSJEyhYcAjY1btIWlCtF6o60A9SX7RxaHe1THYAUifCtVfkaApB5EALw_wcB

[31] https://www.vox.com/a/new-economy-future/manual-labor-luxury-good

[32] https://www.marketsandmarkets.com/Market-Reports/telepresence-robot-market-146812674.html

a. Augmented work (1-5 years) - Ability to help humans punch above their weight with augmented capabilities will make new jobs or capability open up for us. So a nurse might be able to make better doctor-like decisions and even help perform minor surgeries with help of robot assistance.
b. Mapping opportunities intelligently (2-7 years) - With current matchmaking systems (say linkedin or employment platforms) only matching 2% of total jobs available, better understanding of skills and human capabilities will allow for building new matching platforms with remote working built in, which will in turn be unlocking more jobs to the tune of $3T+ of new economic value (Mckinsey research).
c. Shift from work to fulfillment (5-15 years) - As cost of living comes down and UBI (Universal Basic Income) takes, human workers will shift towards working to fulfill their potential, rather than just for economic reasons. As such, a skilling and learning platform for creating unique skilling and talent mapping opportunities will emerge.

Defense & Cybersecurity

The report on future of warfare in 2030[33] by Rand Corporation, recommends that:

"*Future conflicts will likely place a premium on being able to operate at range. Staying outside adversaries' missile ranges and basing from afar both could be important factors, and the U.S. military should invest in these capabilities.*"

and

"*Because of the trend toward greater use of artificial intelligence, the military will need to invest in automation*."

While these recommendations are for the US military, they are equally applicable to ours. Limiting casualties on our side and limiting civilian casualties via precision strikes, will require development of advanced, connected robotic systems.

In defence, the core aspect of centralized command and control is getting flipped with Autonomous Intelligence. While earlier model used to rely on a few smart people making the decision, now the intelligence with AI is moving closer to the action, allowing edge intelligence to enable faster response for cybersecurity & defense with 4 major objectives (detailed out in figure 3),

i. Enabling intelligent warfare
ii. Enabling remote warfare
iii. Enabling cyber-warfare

[33] https://www.rand.org/pubs/research_reports/RR2849z1.html

iv. Enabling AI-driven security & defense capability with predictive response

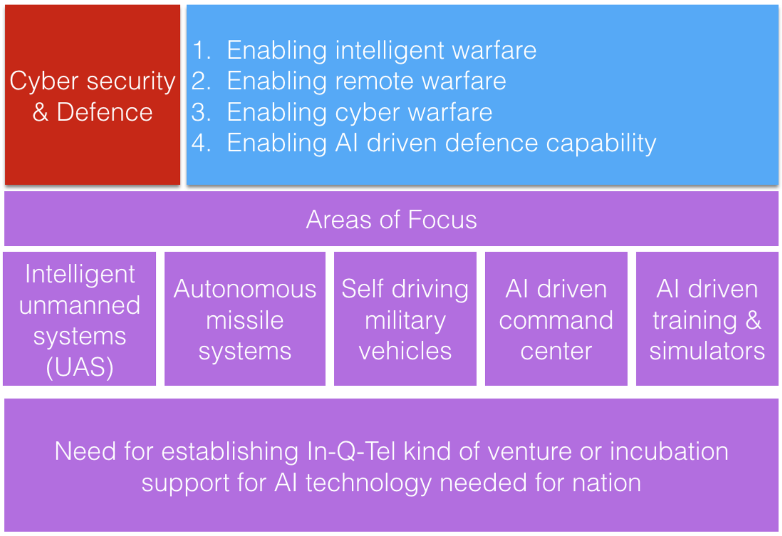


Figure 3: *AI driven cybersecurity & warfare*

As such to achieve the above four objectives, we would have deeply invested in,

i. High definition location Intelligence - Digital high definition mapping is now critical for both men, material and logistic movements. Hi-definition maps are going to be even more important for future mobility of both autonomous and semi-autonomous vehicles and systems (Robots and TeleRobots). Owning our living breathing map is a critical need of the hour. Location data getting exposed through devices is a critical risk (See: Strava Case Study). Google maps are now becoming a monopoly and it can be used as a bargaining tool by the US at any point in time, like it is happening with China (Huawei is investing in maps).

ii. Intelligent Operating system: Android operating system is very leaky and given that it is going to be the base operating system for devices in India is a critical security risk. It makes sense for India to create an intelligent operating system for mobile, devices and eventually a real-time operating system (for Robots and Autonomous systems).

iii. *Intelligent unmanned systems*; both on the ground, water as well in the air, as the increasingly first line of defense is going to be unmanned. This would be flying air autonomous vehicles for logistics, people and arms, as well as autonomous rovers in waters to autonomous trucks and armored vehicles. With 5G connectivity, some of these would be teleoperated as well.

iv. *Autonomous missile systems*; both for warfare and defense as AI intelligence on the edge, coupled with robust computer vision and sensing would enable capabilities that were thought impossible, especially with real-time reactions to ground realities.

v. *Self-driving military vehicles*; on ground and water would enable increasingly swift and 24.7 responses for defense and surveillance.

vi. *AI-driven command center*; which would augment or replace human-driven command centers & would have the ability to predict ahead possible outcomes to plan movement. This would be connected to ground and aerial sensor inputs for real-time response capability

vii. *AI-driven training & simulators*; most of the black swan events that actually happen on the battlefield are hard to emulate on traditional simulators. However, AI-driven training and simulation would make soldiers ready for battle much faster with their added advantage of unpredictability.

Areas of focus in Security & Defense

Furthermore AI is also allowing new ways of looking at operations and strategy specifically for (Figure 3. A new pathway for AI-driven security & defense),

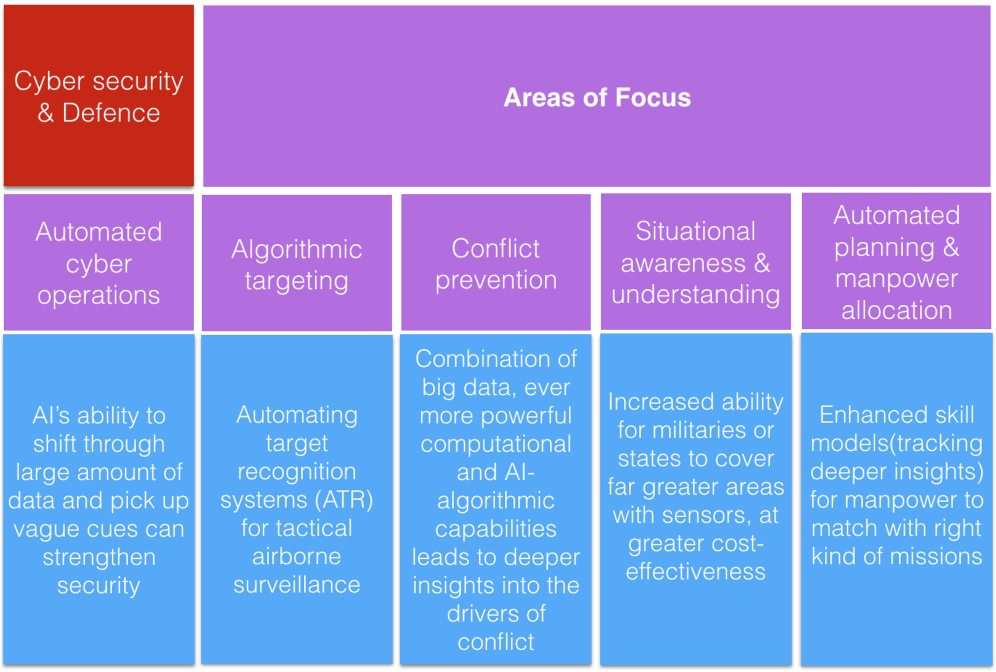


Figure 4: *Prime areas of focus in security & defense*

a. *Automated cyber operations* – Combined with human perspectives, AI's ability to sift through prohibitively large quantities of data, and pick up on vague cues can strengthen security: for instance, Distil Networks uses machine learning algorithms to begin to defend against Advanced Persistent Threat bots, whose interactions are normally difficult to discern from real human users; likewise, Google and the behavior analytics company Gurucul each separately have developed artificial intelligence-based approaches to cybersecurity based on user and risk profiles instead of human-defined rules.

b. *Algorithmic targeting* – With computer vision becoming highly accurate, most of the radar systems would start combining it with vision sensing capability as well. Start-up Deep Learning Analytics, for instance, has developed a machine-learning-based ATR program prototype for DARPA, to trial systems assisting pilots in finding and engaging targets. This is part of DARPA's Target Recognition and Adaptation in Contested Environments (TRACE) research program, which seeks to deliver an accurate, real-time, and energy-efficient target recognition system that can work with existing radar systems, to provide long-range targeting capabilities for tactical airborne surveillance.

c. *Conflict understanding and resolution* - Our ability to track and understand the dynamics that lead to either strengthened or weakened societal resilience based on a combination of big data, ever more powerful computational and AI-algorithmic capabilities is likely to increase exponentially. As such, the most profound and deep use of AI is going to be in combining deep inputs to create a deeper understanding of conflicts and rearrange variables and actionable outputs to prevent them from developing into a crisis. This fundamental shift in how we look at conflicts with perspectives from data could change the future of human society and prevent existential scenarios from developing.

d. *Situational awareness & understanding* - Increasing the autonomy of unmanned systems will strengthen their survivability, enable more higher-end performance, and improve their effectiveness at patrolling or monitoring areas. This feeds into an increased ability for militaries or states to cover far greater areas with sensors, at greater cost-effectiveness than human troops. The enhanced situational awareness enabled by more autonomous and survivable drones can strengthen the security of bases and also result in a deeper grasp of ground conditions.

e. *Automated planning & manpower allocation* – AI & machine learning systems working from datasets of soldiers' capacity tests and their past mission performance (individually and in different constellations of teammates) on different types of missions, could formulate elaborate models. On the basis of these, commanders could gain a comprehensive assessment of an individual's skills, experience, personality, strengths, weaknesses or psychological condition. Machine learning systems could also help them align human talent to mission requirements, and optimize team composition for specific missions, based on expertise & personality, or past unit performance under different conditions.

Mining & Retail

The mining industry has started adopting autonomous vehicles[34]. Companies like Volvo, Caterpillar, etc. have developed autonomous truck technology to address this market. Mining areas have very few people and vehicles around and hence a good trial ground for autonomous vehicle technologies. Similar opportunities for using autonomous vehicles for moving materials exist in other scenarios - like construction of highways, bridges, etc., especially in remote locations. The retail industry also offers enormous opportunities for autonomous systems and robots - from remote checkouts, autonomous stores to robotic vehicles for moving items between warehouse to shelves, to service robots to interact with customers[35], and even to make deliveries in the neighbourhood[36] via drones. Online retailers will move even closer to customers with completely automated warehouses built for robots, which will be much smaller in footprint allowing for faster delivery times for customers.

Agriculture

Agriculture is a critical application vertical with more than 50% of Indian population involved in agriculture production. Innovation is important for improving the GDP contribution of agriculture. There are a few major areas of innovations, which are worth exploring:

a. Autonomous systems driven agri supply chains (1-5 years): Major challenge in agriculture is that 1/3rd of the produce is wasted. As such, sensor driven networks coupling the demand side with the supply chain to map real-time and predictive supply chain feedback is going to be key to reducing the wastage and also helping farmers produce things that are needed.
b. Autonomous agro processing technology (2-7 years): Indian farms are small and produce is limited, as such creating technology for small batch agro processing for farmers can allow them to quickly convert their excess crops or produce to higher priced processed or packaged products.
c. Tele Robotic farming (2-9 years): Robotic farming is picking up steam in developed countries, due to shortage of labor and the size of their farms. Robots have an opportunity to be used in all aspects of farming: from planting and seeding, to picking and harvesting and for shepherding of livestock[37]. While at first shot it might seem politically incorrect to advocate robots for farming

[34] https://www.wardsauto.com/industry-voices/mining-industry-laboratory-self-driving-tech
[35] https://www.wns.com/insights/articles/articledetail/515/robots-in-retail-driving-innovation-one-aisle-at-a-time
[36] https://ottopia.tech/
[37] https://blog.robotiq.com/top-10-robotic-applications-in-the-agricultural-industry

in India, a closer examination will reveal that there are tremendous gains to be had, without affecting the labor market. Several Indian farmers are already adopting drone technology for assisting with monitoring, spraying, etc. Some of the farms for produce like arecanut, coconut, etc. are suffering from shortage of skilled labor for harvesting. However, the introduction of robotic technologies and training of laborers to operate them, will be a win-win for everyone - increasing efficiency of production, as well as providing better quality employment to farm labor. With tele-robotics, the labor skill can also be transported across space - without having migrant workers moving from one state to another.

5.1. Technology Innovation Missions

Our hub will undertake Technology Innovation Missions that have potential for

1. Large Societal Impact - This is critical as we envisage a larger and deeper impact for the technology created. This focus will also force us to think applications from a large scale perspective and make a marked change in the lives of people. Societal impact is also critical from the perspective of the need of key stakeholders such as the government,
2. New deep technology inventions to enable new talent creation and strategic value to all stakeholders. These new areas will also help create new knowledge creation with the collaborating institutes, and
3. Economically sustainable deployment/delivery of solutions to create larger impact by IP and research translation will allow for the institute to become self-sustaining over the next few years. It will also serve as a forcing function to create strong market driven IPs and technologies.

as depicted in Figure 3.

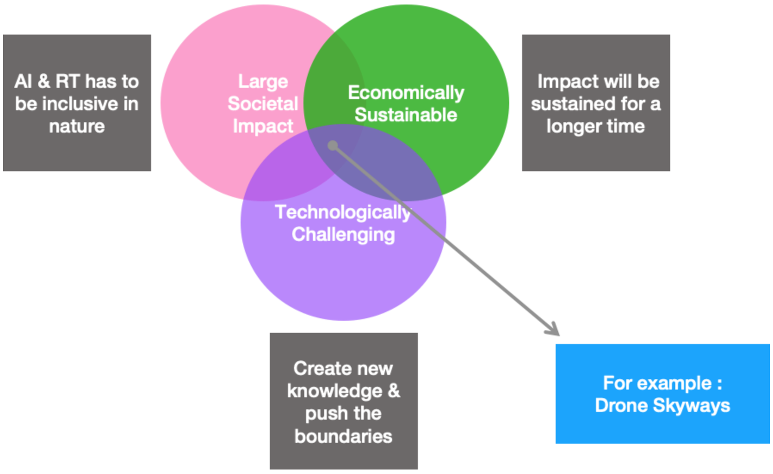


Figure 3: Technology Innovation Projects will be chosen based on triple impact

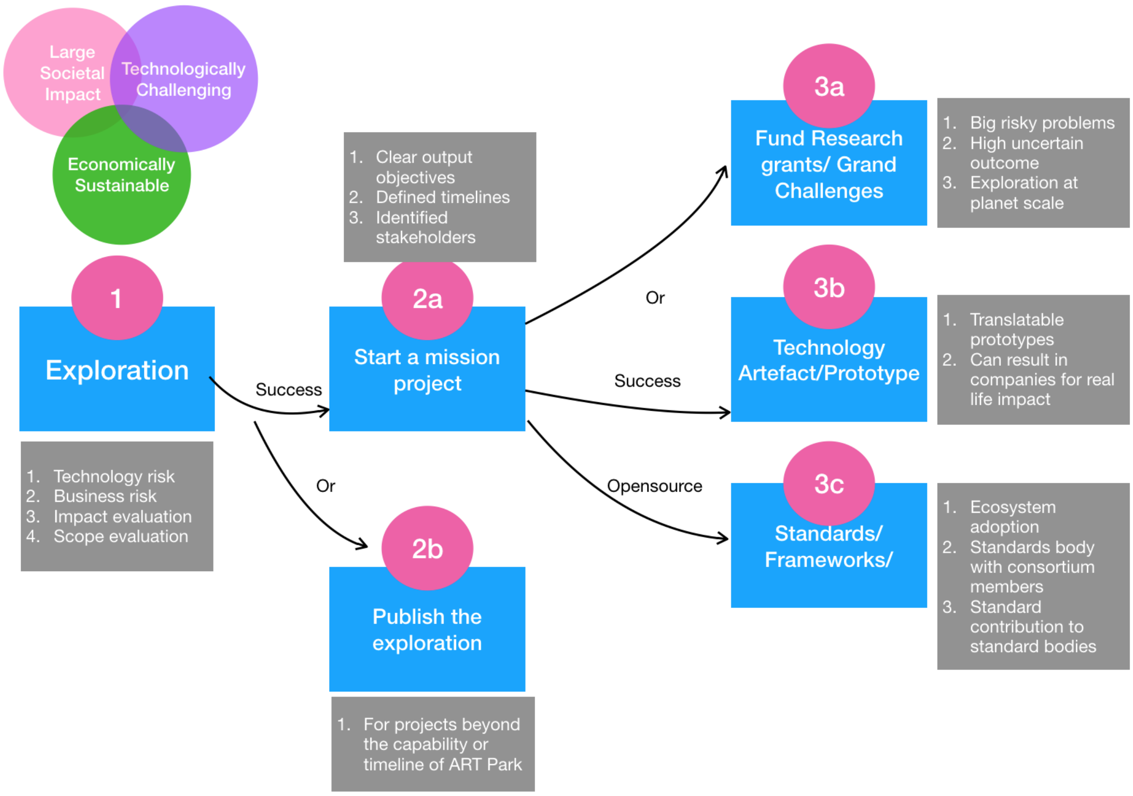
Mission cycle :-

Key challenge in such an open environment is to look at what problems could fulfill triple impact criteria. So we define a 3 step process for the mission cycles,

a. Exploration phase - In this phase, we assign limited man power, time (90-180days) and resources to ideas and problem spaces, to distill out key technology risks, business risks, impact evaluation criteria and scope. This is also to assess the key stakeholders required for engagement. Exploration phase could lead to a mission, with defined output objectives, timelines and mapped to key stakeholders and their requirements. If explorations result in out of bound problems, it can be published like an open challenge for others to build on.
b. Mission phase - Mission phase is to turn the successful explorations into full fledged missions. At this phase, we build the full blown mission team around the key people leading the mission, create the success metric and help raise further funding to graduate it from validated research

ideas to technology artefact, prototype or standards/frameworks. Mission will be output and timebound. Incase mission fails to achieve the objectives with ARTPARK's resources, it can be turned into open source problems for others to take and solve or if the problem turns out to be too deep, it can be converted into grand challenges.

c. Translation phase - Translations phase involve turning mission IPs and outputs into products or companies (both for profit and not for profit) for great impact via. Innovation/ Venture studios, licensing to other established companies or govt. Such translations will be supported by grant, venture funding or other support for faster impact.



The four key roles of the hub will be:

a) Identifying such missions will be a key task of the Hub, and will be done via a consultation process involving key stakeholders.
b) Once the missions are launched, providing them with mentorship, critical reviews and networking support, will be the second key role of the Hub.
c) Finally, as the mission starts producing technology and IP outputs, finding ways to translate them to the outside world via startups, open source, standards, etc. will be the third key role of the hub.
d) Finally, the hub will also actively look for new collaboration partners, funding sources, and appropriate manpower talent to feed the technology missions.

5.2. Operations

Table 1 summarizes the expected outputs from this hub over the coming five year period. These are mainly along two different axes: a) Human Resources (HR) output and b) Technology, IP and Impact outputs. Existing frameworks in government, academia and industry are good enough to support these independently. The real challenge for the hub is to do both simultaneously, and in a manner such that they feed off each other.

Innovation + Translation Funds	
30%	70%

<table>
<tr><th colspan="2">Innovation Program</th><th colspan="2">Translation Program</th></tr>
<tr><td rowspan="3">Calls</td><td colspan="2">Grand Challenges & Competitions</td><td rowspan="3">Calls</td></tr>
<tr><td colspan="2">Call For Pathfinding & Proof of Concept Proposals</td></tr>
<tr><td colspan="2">Call for Research & Translation Proposals</td></tr>
<tr><td>Review-Mentor Committee Formation</td><td>Review and mentor panel involving stakeholders</td><td>Review and Mentor panel involving VCs and Potential Customers</td><td>Review-Mentor Committee Formation</td></tr>
<tr><td>Selection, Monitoring and Mentoring</td><td>Innovation Projects</td><td>Translation Projects</td><td>Selection, Monitoring and Mentoring</td></tr>
<tr><td rowspan="10">Academic HR Program</td><td>PhD Fellowships</td><td>PhD Fellowships(Business)</td><td rowspan="10">Translation HR Program</td></tr>
<tr><td>Post-Graduate Fellowships</td><td>Post-Graduate Fellowships (Business)</td></tr>
<tr><td>Graduate Fellowships</td><td>Young Entrepreneur (PRAYAS)</td></tr>
<tr><td>Post-Doctoral Fellowships</td><td>Entrepreneur/Technologist-In-Residence</td></tr>
<tr><td>Faculty Fellowships</td><td>Industry Mentors-in-Residence</td></tr>
<tr><td>Chair Professors</td><td>Chair Professors (Business)</td></tr>
<tr><td>High End Skills Development/Interns</td><td>Technical Mentors-in-Residence</td></tr>
<tr><td>Skills Enhancement Courses</td><td>Technopreneurship Certificate Program</td></tr>
<tr><td>Annual Tech Symposium, Newsletters, Instructional Workshops,Blogs</td><td>Visioning Workshops, Networking events, Blogs, PR</td></tr>
</table>

Table 2: Strategy and Operations table.

In order to attack this problem, we plan to have two inter-related threads of activity, also called as programs in the hub (Table 2):

a) Innovation Program: This will focus on creating innovative solutions fed by deep academic research
a) Translation Program: This will focus on converting proof-of-concept demonstrations of novel solutions into technologies and products.

Each program will have a single person in-charge, but with an appropriate panel to guide and support and a small execution team to help its implementation. The two panels will have some common members so that the programs don't become siloed. We plan to allocate about 1/3rd of the recurring funding for the innovation program and 2/3rd to the translation program.

5.2.1. Innovation Program

The Innovation Program will be largely carried out by academic researchers consisting of faculty, students and research project staff. They will focus on creating innovative solutions backed by rigorous scientific and engineering methods. We propose to allocate about 30% of operational funds to support this program. The key elements of this program are described next.

5.2.1.1. Calls

Based on stakeholder interactions, market analysis and IP analysis, specific gap problems, with sufficient technological depth will be identified. To address these gaps with innovative technology solutions, calls for proposals will be issued in three forms:

5.2.1.1.1. Grand Challenges & Competitions:

Grand challenges and competitions along the lines of that conducted by Xprize[38], will be held annually. A substantial prize money will be made available to get serious interest from participants. The challenge will be conducted in a professional manner, over a period of 2 to 3 years to allow sufficiently deep solutions to emerge open to everyone.

Pathfinding proposals: We will also issue calls for path finding proposals. These will be shorter duration and will involve exploratory projects between 3 to 6 months. The output of these activities will be identification of new problems/gaps and potential solution directions, in the areas of interest to the hub.

Research Proposals: Once clarity on the broad problem statements is achieved (either via stakeholder consultations or pathfinding proposals), full blown research proposal calls will be issued. However, these will be jointly issued with the translation call, in order to ensure a good coupling between the two activities and focused on 1-3 year horizons based on continuous research and continuous translation model with iterative feedback loop between both of them.

5.2.1.2. Panel

This will consist of select faculty members form IISc as well as other researchers and technologists from Industry. Some of the panelists will also be part of the translation panel - in order to allow for a good cross-pollination.

5.2.1.3. Mentor and Monitor

Every activity will have a review committee and longer duration activities will also have the review committee act as a mentor panel. While care will be taken during selection of good proposals, once a project is started, the purpose of the panel will be more to provide critical feedback and mentorship enabling a successful completion. Yearly check points will allow continuous adaptation of the targets.

5.2.1.4. Human Resources Development

The funding support for fellowships to students, post-docs and faculties, will be in-line with the support for research projects. This will ensure that there is good alignment of the research and HR deliverables.

5.2.1.5. Outreach

Publications and presentations in high quality international conferences and journals will be encouraged and supported. The innovation manager will also conduct a yearly symposium to showcase the research done in TIH sponsored projects. In addition, periodic newsletters, blogs, etc. will be written to showcase the research.

5.2.2. Translation Program

The Translation Program will be largely carried out by staff in the TIH. Their focus will be to create technologies (possibly based on academic research)that can be easily deployed in the real-world. This work will be driven by engineers and professionals with sufficient background and experience in Industry. The key elements of this program are described next.

5.2.2.1. Calls

These will be done in sync with the Innovation Program’s call.

[38] https://avatar.xprize.org/prizes/avatar

5.2.2.2. Panel

The panel here will consist of people from Industry and the Venture Capital community mainly.

5.2.2.3. Mentor and Monitor

Mentorship and monitoring will be with an eye towards converting each of the projects into a successfully incubated startup. Best practices from SRI, MILA, MIT Media Labs and other such places will be studied and adapted.

5.2.2.4. Human Resources Development

A few of the student and faculty fellowships will be reserved to support members from business schools. These will be a small fraction of the overall fellowships - but will encourage study, documentation and knowledge creation around the innovation process. IIM Bangalore could be a good partner for us in this adventure, but we will also explore tie-ups with other business schools. The MBA students and incubatees from there can be co-opted to join the translation team - to provide business and marketing heft to the activities.

5.2.2.5. Outreach

Visioning workshops, networking events etc will be conducted periodically (one will be done annually in coordination with the tech symposium). In addition emphasis on social media based outreach via blogs, newsletters, market reports, etc. will be done to connect with the outside ecosystem.

6. Target Beneficiaries

Successful implementation of the hub will benefit a diverse set of stakeholders as follows:

IISc: The hub will bring in cutting edge, high impact technology problems for our faculty and students. The resultant facility creation will allow for state-of-the art training of students as well as cutting edge research publications and technology & IP outputs.

Collaborating Institutions: Collaborating institutions will

a) Get a connection with Bangalore/Karnataka/India ecosystem in High-Tech and Venture space.
b) Participate with the hub/IISc to jointly respond to funding calls
c) Exchange students and researchers between the Hub/IISc and their institutions
d) Benefit from the state-of-the-art facilities for their own research and academic programs.

Founding Member Companies: Founding member companies will invest a specified amount into the hub and in return

a) Have a seat in the governing board and be able to shape and closely participate in the hub's activities
b) Benefit from the facilities, expertise and talent at the hub/IISc.
c) will have benefits from IP licensing and translational objectives, which will be detailed post interactions.

Partner Companies: Partner companies will support one or more activities of the hub via collaborations in terms of participating in a project via one or more of:

a) partial funding support

b) providing some sweat equity in terms of man-hours from their employees

c) provide tools or materials to execute the project/activities

The partner companies will benefit from the expertise, facilities and talent at the hub and IISc to enhance their own products and solutions.

Government: Karnataka and Central government will benefit from the talent creation as well as the boost to the economy through the startups enabled by the hub. In addition strategic technologies will get created which will be of great use to the country.

6.1. Probable Industry/Academic Collaborations

Airtel, Nokia, Cisco, Garrett, MIT, IITK, IITB are potential collaborators

7. Legal Framework

IP Policy

In all the hub-funded projects carried out by academic institutions, the hub will jointly own the IP with the academic institution. The IP policy framework will be benchmarked with global institutions such as MILA, SRI, ETH, KTH, MIT MediaLabs and others, so that it is able to create a self sustaining future over a period of time, at the same time creating a very efficient environment for an "idea to impact" research translation engine.

The hub will endeavor to secure grants from funding agencies (governmental or industry), in a manner which gives it the maximum flexibility to support successful translation of any IP or technologies that is generated with the partnering institutions.

Partner agreements

Draft MoA/AoA and MoUs are under preparation.

8. Environmental Impact

EIA is usually applied to individual projects. At a company policy level we will have a Strategic Environmental Assessment (SEA) plan which will apply to all projects taken up by the TIH. This will evaluate the applicability of EIA to individual projects and then do an assessment based on the requirements of the particular project.

The primary laws applicable for an EIA are the Wildlife Protection Act (1972), Water Act (1974), Air Pollution Act (1981), Environment Protection Act (1986) and the Biological Diversity Act (2002).

Every project undertaken will look at the applicability of the above and then do an analysis accordingly.

We plan to set up two outdoor facilities for robotics and autonomous vehicle research. A smaller one will be set up in IISc's main campus in Bangalore. A larger one will be set up in IISc's Challakere campus in Chitradurga district of Karnataka. These facilities will have some civil work and the larger drone related facility in the second campus might have an impact on the birds. These will be duly considered while setting the facilities, so as not to have any significant impact.

ARTPARK will also look at how technology can make a positive impact on the environment. For example delivery by drones can reduce the carbon footprint for a delivery and also lower vehicular congestion on roads which decreases the overall carbon footprint and pollution. The international Carbon Credits market has largely been stagnant in recent years but the Kyoto Protocol's Clean Development Mechanism has significant value. If any of our projects have applicability in that framework then we will certainly work towards that and the relevant certification and sale.

9. Technology

A key value proposition of the TIH will be a Robotics and Autonomous Vehicles testbed facility, set up at three scales: Indoor, Small Outdoor, Large Outdoor. The indoor facility will have Robot Arms, Humanoid and Legged robots supplemented by various instrumentations for experimental evaluations. The small outdoor facility in IISc main campus will span a few acres. It will have a wind shaping facility as well as an indoor flight space for testing small air and ground vehicles. An outdoor testbed will allow testing of small to medium ground vehicles at low speeds. The large outdoor facility will span multiple acres and will be set up in IISc's Challakere campus. It will allow testing of larger air vehicles as well as ground vehicles at higher speeds. More details on the test facilities are in Appendix A.

A second virtual facility will be for a data testbed to collect, maintain and share data sets related to the themes and missions of the hub. This data testbed will be set up to be privacy preserving, including elements of confidential computing, federated learning and tools for data governance. More details are in Appendix B.

In addition to the testbed facilities, we plan to start four exploratory mission projects on

a) Drone Skyways, which aims to develop technologies for urban drone corridor networks and demonstrate (via a pilot) an urban air corridor for drones in a smart city, with an aim to support delivery of small goods (like food items, medicines, et. within a city). Develop counter drone technologies for detecting and neutralizing rogue drones. (Appendix C)

b) Autonomous Ground Vehicles, which aims to develop technologies for Level 4 autonomous mobility of vehicle fleets, to operate in unstructured yet restricted environments and demonstrate in a pilot setting that will emulate scenarios with low vehicular and people density – like campuses, construction sites, ports, docks, etc. (Appendix D)

c) Tele-Robots, which aims to develop technologies for control and supervision over networks for machines to operate semi-autonomously, including mobility and interaction. This will be demonstrated via remote driving and operation of machinery for industrial applications as well as remote social interaction through an android, with a view to enable applications like remote nursing, hands-on teaching etc. (Appendix E)

d) Microbots, which aims to develop technology solutions addressing the core problems of modern micro-robotics, especially those related to their deployment in biomedical applications. The specific challenges to be dealt are related to (i) powering and imaging remotely manoeuvred micro/nanobots deep inside an animal, (ii) on-board electronic and MEMs devices for both in vivo and ex vivo sensing and signal processing, and (iii) controlled assembly and analysis of living cells combining microfluidic and MEMs technology platforms. (Appendix F)

10. Management

The three key executives in the TIH will be:

a) Chief Executive Officer (CEO) will be the overall head of operations of the hub. His/Her main responsibilities will include:
   i) Raise funding via grants from CSR, governmental and other non-governmental sources.
   ii) Network with key stakeholders and funding agencies to ensure continued alignment with objectives
   iii) Oversee the TIH's operations to ensure that it meets its key objectives
   iv) Evangelize TIH's activities to get high visibility and impact
   v) Help in conducting the Hub Governing Board meetings and presenting the TIH's status and future plans.
   vi) Develop and manage the business strategy for self-sustenance of the hub.

   The CEO will Report to the Board of Directors of the company.

b) Chief Research Officer (CRO) will be incharge of the Innovation Program of the hub. His/Her main responsibilities include:
   i) Identify topics for technology strategy, Innovation Calls, via consultation with key stakeholders and the CEO and COO
   ii) Issue and manage Calls/Grand Challenges to identify new projects in identified themes
   iii) Set up review and mentoring committee for ongoing funded projects and manage the life cycle of such projects
   iv) Conduct regular tech symposiums, publish newsletters and blogs.
   v) Run the academic fellowship program to identify and fund students and faculties, in order to further the objectives of TIH's innovation and translation programs.
   vi) Manage the high-end skills development program in collaboration with IISc.

   The CNO will report to the CEO. The CNO will be aided by a Innovation Program Committee consisting of select faculty from IISc as well as researchers from academia and industry.

c) Chief Operating Officer (COO) will be responsible for running the translation program. Her/His main responsibilities include:
   i) Identify the translation opportunities in consultation with CEO and CRO and the participants in the ongoing technology innovation missions
   ii) Issue calls/competitions for identifying translation projects
   iii) Manage staffing for the entrepreneur-in-residence, young entrepreneurs and technologists-in-residence, to further the translation goals of the hub.
   iv) Set up review committee to mentor and review the ongoing translation projects
   v) Conduct regular visioning workshops. Publish newsletters, blogs and manage Public Relations.
   vi) Identify and hire industry mentors-in-residence and fund business school phd and faculty fellowships to further the objectives of TIH's innovation and translation program.

   The COO will report to the CEO. The COO will be aided by a Translation Program Committee consisting of practitioners from industry and investment firms.

Support administrative staff will help with the operations. All other staff will be hired as per the needs of the ongoing programs and mission projects and will support a flat horizontal structure of tightly bound mission teams.

The Statutory Board of Directors will consist of:

a) Director of IISc (ex-Officio) (Chair of the board)
b) Chairperson, Division of Interdisciplinary Research (ex-Officio)
c) Chairperson, Robert Bosch Center for Cyber Physical Systems (ex-Officio)

The Hub Governing Board will be the apex body which will determine the strategic directions of the hub and will consist of:

a) Director of IISc (ex-Officio) (Chairperson of the board)
b) Chair, Division of Interdisciplinary Research, IISc (ex-Officio)
c) Chair, Robert Bosch Center for Cyber Physical Systems, IISc (ex-Officio)
d) DST Representative (ex-Officio)
e) AIOT Foundry Representative (ex-Officio)
f) One representatives from other founding member institutions
g) Other Funding stakeholders both govt. & non. Govt. & other invitees of global eminence .
h) CEO (member secretary)

11. Finance

11.1. Budget Ask from DST

Budget Head/ Year	Year-1	Year-2	Year-3	Year-4	Year-5	Total
Recurring	13.25	33	50	25	9.75	131
Non-Recurring	9	13	6	6	5	39
Total (in INR Crores)	22.25	46	56	31	14.75	170

11.2. Overall Budget

The budget for expenditure outlay is summarized in this table:

ARTPark Foundation (in INR Crores)	Y1	Y2	Y3	Y4	Y5	
NRE						
Facilities (DST)	9	13	6	6	5	**39**
Facilities (GoK)	6	5	1.5	0.5	0.5	**13.5**
RE						
Skills Development (DST)	0.25	3	3	3	3	**12.25**
Skills Development (GoK)	0.9	0.9	0.9	0.9	0.9	**4.5**
International Collaboration (DST)	0	10	10	10	0	**30**
International Collaboration (Other)	0	0	24	24	40	**88**
Technology Innovation (DST)	11.75	16.5	31.5	6.5	5.25	**71.5**
Technology Innovation (GoK)	3	5.5	8.5	9	7	**33**
Technology Innovation (Other)	0	**10**	**15**	**15**	**20**	**60**
ARTPark Venture Studio (DST)	1	3	5	5	1	**15**
ARTPark Venture Studio (GoK)	0	1	1.5	2	4	**8.5**
ARTPark Operations (DST)	0.25	**0.5**	**0.5**	**0.5**	**0.5**	**2.25**

ARTPark Operations (Other)	0	1	3	5	7	**16**
Total (DST)	**22.25**	**46**	**56**	**31**	**14.75**	**170**
Total (GoK)	**9.9**	**12.4**	**12.4**	**12.4**	**12.4**	**59.5**
Total (Others for ARTPark)	**0**	**11**	**18**	**20**	**27**	**76**
Total	**32.15**	**69.4**	**86.4**	**63.4**	**54.15**	**305.5**

11.3. Revenue/Grants

The revenue/grant budget is summarized in this table:

Funding Organization/Year	**Y1**	**Y2**	**Y3**	**Y4**	**Y5**	
DST	15	46	56	31	14.75	**162.75**
GoK	10	12.5	12.5	12.5	12.5	**60**
DST Initial release to IISc	7.25					
Others	7.15	10.9	17.9	19.9	26.9	**82.75**
Total	**39.4**	**69.4**	**86.4**	**63.4**	**54.15**	**305.5**

One of the priorities for the CEO will be to raise additional money from various sources to cover for this gap.

11.4. HRD Skills Development Budget

Item	**DST Numbers (5 Years)**	**ARTParkNumbers (/yr)**	**Renumeration (Lakhs)/Yr**	**Unrestricted Research Grant (Lakhs) /Yr**	**Total (Lakhs)/Yr**
High End Skill Development (Associates)	1020	204	1	0	204
Graduate Fellowships	340	68	3	0	204
Post-Graduation Fellowships	62	12.4	5	0	62
Doctoral Fellowships	25	5	8	2	50
Post Doctoral Fellowships	0	0	12	3	0
Faculty Fellowships	6	1.2	20	30	60
ARTPark Chair Professor	6	1	30	50	80

Total					**660**
Management					
Lead	1		30		30
Associate	1		12		12
Assistant	2		8		16
Running Expenses					25
Delivering content and courses					100

11.5. TIH Operations Budget

	As Percentage of Total Fund Raise	**INR lakhs**	**INR crores**
Salary Budget for Apr - Sep 2020		0	0
Salary Budget for Oct 2020 - Mar 2021		1207	12.07
Rentals for Physical Location for 11 months (May 2020-Mar 2021)	Monthly Rent in INR lakhs (all inclusive		
SID 2000 sq ft space	2	22	0.22
City Space 6000 sq ft	8	88	0.88
All the Below are for Full FY 2020-2021			
Legal Cost		15	0.15
Website Building & Hosting Cost		4	0.04
Section 8 Setup and Permissions Cost		5	0.05
Finance, Auditing and Regulatory Cost		20	0.2
IP Policy Formation Cost		7	0.07
Patent Filing Cost+Retainer		32	0.32
Marketing Budget (Marketing of ART Park for Potential Sponsors and Collaborators)	1.00%	150	1.5
Travel (Flights + Accommodation + Food)	1.00%	150	1.5
Events Budget (For Events/ Conferences to be held by ART PARK)	0.50%	75	0.75

External Conference Budget (Registration Fee, Travel, Food, Stay etc)	0.50%	75	0.75
Mission Budgets (for ART Park Funded Projects for Public Good)		500	5
Mission Exploration Budgets (50 lakhs each)		500	5
IT Purchase Budget (Laptops+others)		297	2.97
IT Servers + Compute		500	5
Collaborative Research Budget (Domestic (IISc)+ Foreign Universities and Institutions)		1000	10
Facilities for Dedicated Missions			
Four Level Robotics and Autonomous Systems Facility		2665	26.65
Datasetu facility and databanks		500	5
Utilities Mapping		500	5
Recurring			
Non recurring			
Miscellaneous and Administration		66.5	0.665
TOTAL SPEND BUDGET		**8378.5**	**83.785**
Operaitons (all above except facilities and salary)		3506.5	35.065

11.6. Facilities: Warehouse Robotics Testbed

Item	Min. Qty	Description	Possible Vendors	Estimated Cost (INRLakhs)
6DOF Collaborative Arm	2	Arm for collaborative robotics	DENSO, ABB, Kuka, UR	60
6DOF Industrial Arm	2	Normal industrial robot arm	Systemantics, Yaskawa, Dobot	30
3DOF Mini Arm	4	Desk top model	Systemantics, Dobot	10
3D Printers	2	High end 3D printer	Ultimaker etc	30
Consumables	NA	Motors, Drives, Actuators	Different Sources	100
VR Kit	2	Virtual Reality Kit	HTC, Oculus	10

AR Kit	2	Augmented Reality Kit	Atheer	20
Humanoid Robot	1	Humanoid Robot with Facial Emotion Engine	Hanson Robotics	60
Small Humanoid Robots	2	Smaller humanoid robots	Nao	25
Small Mobile Bots	10	Small indoor ground vehicles	Turtle Bots etc	50
Minibots		Miniaturized mobile bot kits	TI etc	15
Sensors (Lidars, mm-wave radars, Stereo cameras)	NA	Sensors of various kinds to be mounted on vehicles, as well as embedded in infrastructure	Different Sources	200
Total				**610**

11.7. Facilities: Dronery Budget

Item	Description	Cost (INR Lakhs)
Windshape Modules	Fan array modules	200
Power Supply	Power supply Units	60
Control units & Software	Control of Fan modules and associated software	40
Civil Infrastructure	Shed, Nets, other ancillaries	70
MoCAP system	Tracking of drones	70
Communication Network	5G and WiFi6	100
Total		**540**

11.8. Facilities: Mini Test-Track Budget

Item	Description	Cost (INR Lakh)
Civil Cost	Installation of poles, creation of test track	15
Next Gen Wireless Equipment	5G and WiFi6	150
Electronically Controllable Vehicles	Software/Electronically controllable vehicles - small and medium size	50
Sensors for localization and tracking	Radar, Stereo Cameras, Lidar,etc	100
Total		**315**

11.9. Facilities: Large Test-Track Budget

Item	Description	Cost (INR Lakh)
Civil Work	Setup road test track and other supporting infrastructure	400
Radar, tracking and signalling, Scada, AR/VR, HCI equipment	Track drones and vehicles, Human computer interface	200
Next Gen Wireless Equipment	5G and wifi6	300
Maintenance Garage	State of the art equipment maintenance facility	100
Simulation Framework	Software and compute infrastructure	100
Air Vehicles	Micro, Medium and Large Sized Air Vehicles	400
Ground Vehicles	Small, Medium and Large sized ground vehicles	500
Total		**2000**

11.10. Facilities: Data Setu

Item	Description	Cost(INR Lakhs)
On-Prem Compute and Storage	GPU, CPU, NAS, NetworkEquipment, High Speed Leased Line	100
Data set creation for Maps	high definition maps	250
Data set creation for Robotics	Video, Audio, Demonstrations	50
Data set creation for Navigation	Indoor and outdoor driving and navigation for vehicles	100
Total		**500**

12. Time Frame

Major tasks and quarterly timelines are shown below.

	1.1	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4	5.1	5.2	5.3	5.4
Hiring Senior Executives																				
Setup of TIH and hiring admin staff																				
Initial Staffing with Technologists-in-Residence																				
Completing MoU with IISc and TIH																				
Starting Exploratory Projects and awards for fellowships																				
Review of Exploratory Projects																				
Identification and Start of Mission projects																				
Annual review of Mission Projects																				
Startup Spinoffs																				
Annual Tech Symposium																				

13. Cost Benefit Analysis

Cost Benefit Analysis is relevant at two different levels.

The first is for selection of a problem/ project to be taken up at ART Park.

The second is for the commercialisation of a new technology once it has been developed at ART Park

For a Public Good/ Social Sector project the size of the problem should be large enough and relevant to India. Potential benefit to the country will be one of the most important criteria which will be used for this analysis. Projects which might or might not show a clear economic benefit for the Inventor/ Technologists but have enormous economic benefits for the nation will be some of the most important problems which we will look at.

Below are some examples of use cases which might be taken up at ART Park. All of these problems have very large applicability and most can be potentially taken up on a global scale.

- Current Google Maps do not map many important layers like utilities, water pipes, electricity lines etc. and whatever layers they have like roads, traffic patterns etc. they do not share with external parties including govt. bodies. We at ART Park believe that these layers need to be mapped and that they can be an important part of enabling better and more efficient governance. The current commercial sales of Google Maps in India is approximately USD 200 mn and growing at 50%+ CAGR.

- Similarly Drones will be a part of the worldwide overall technology ecosystem in a few years from now. If we can build the Framework for how Drones will fly in a congested city then we will not only help our country but will also have a potential technology which can be used across the entire world.

- In India almost 60% of water supply comes from groundwater. However very little is known about the water levels in different seasons and when the wells go dry. Groundwater mapping is much required to understand the state of the aquifers and Artificial Intelligence will be a critical tool for the same. Again the size of the problem can be quantified in 1000's of crores but currently it might not have an established economic model.

- The Govt. of India has shown great foresight in creating the National Smart Cities Mission. Cities form the economic lifeline of not only India but the entire world. We would like to look at some of the critical components of how to make a smart city successful including creating standardised frameworks for storing data and processing it so that other developers can work on top of that to create individual solutions.

For Cost Benefit Analysis of commercialization we should remember that new technology adoption requires a lot of assumptions. The initial cost of any new technology will mostly be high and the cost goes down as scale comes in. So any technology which can be commercialised will be taken out of ART Park in a separate company and the subsequent cost at scale models will be developed outside of ART Park.

While doing Cost Benefit Analysis of new technologies we should look at not only first order effects but also second or higher order effects whenever possible. A classic example of this is the worldwide debate on whether ride sharing cabs actually decreased traffic on the roads or increased traffic by adding too many shared cabs and not reducing enough owned cars.

We will do all of this analysis before taking up any new project and the analysis will be updated on a yearly basis.

14. Risk Analysis

IP Risk

ART Park will have a clear IP Policy which will apply to all projects being done in ART Park. It will also have legal counsel vet all contracts with private parties for sponsored research etc. in which such rights will be clearly articulated

Legal and Contractual Risk

Contracts in India are governed by the Indian Contract Act which is based on English Common Law. ART Park will always ensure that it is adequately covered in all contracts. ART Park will not take unlimited liability in any contract. In general the company will also not take any contingent liability. Even if for a specific purpose the company does take contingent liability it will not be of an unlimited nature and will be capped as necessary.

Environmental Risk

As described earlier, an EIA (Environmental Impact Assessment) will be undertaken whenever necessary on specific project basis. On an overall scale ART Park activities will not have high Environmental Risk

Revenue Risks

Since ART Park is a Section-8 company this item would primarily revolve around Funding Risks and not Revenue Risks. Art Park will prepare a Budget every year based on funds in hand and expected fund raising. Potential projects will be lined up in advance but ART Park will devote significant economic resources to them only when the Funding is in sight.

For some large projects involving infrastructure creation like outdoor facilities for robotics and autonomous vehicle research the work will start only after significant funding has been secured and there is a line of sight for the remaining funds. However it should be noted that such large projects will involve multi-year fundraising and will become fully functional in a stage by stage manner over years.

Project Management Risks

This is mostly not relevant to this company because of the type of projects. For large infrastructure projects like facility creation mentioned above we will follow all standard guidelines.

Regulatory Risks

Some cutting edge technology development might be in regulatory grey areas. ART Park will document and manage that risk for every project by talking to relevant stakeholders in government and other regulatory bodies.

Other than the above we envisage the following Risks which may be relevant to particular projects

Cost and Time Overrun Risk

All the projects in the portfolio are TRL 2-3 stage projects where it is not possible to do definite cost and time estimates. ART Park will continuously monitor and update all cost estimates and timelines on a 6 monthly or yearly basis. Decisions on further continuation/ extension/ pivot or shutdown will then be taken based on these reviews. Note that because of the cutting edge nature of the work most projects may not reach their desired conclusion. The company will prepare literature in future based on actual performance and use this learning in the future.

Execution Risk

Execution Risk will come into play after the product/ technology crosses TRL 5-6 level. It can primarily be divided into 3 categories

1. Product Development Risk: The Technology developed might not transfer smoothly into a product in terms of mass manufacturing. The product also needs to be user proof

2. Dependence on External Capital for Product Development: As discussed earlier the primary purpose of ART Park is to spin out technologies as companies. The Companies thus spun out will need external capital. ART Park will work towards this objective by creating both the Venture Studio and also reaching out to external Venture Capital Funds.

3. Long Execution Time Frame: This is a standard risk for all technology companies and venture/ risk capital is best positioned to address the nuances of this.

Market Risk

Once a product crosses the TRL 6-7 level and is ready to go to market there will always be a market risk in terms of pricing, adoption, competition, distribution channels etc. That is why ART Park will not be involved at this stage and the technology/ product will be spun out as a separate company or given to an external company to further develop and take forward. ART Park can provide some help at this stage but will not be directly involved

15. Outcomes

The outputs in terms of Technology Development, IP Creation and Training will be measured against the targets mentioned in Table 1.

The ultimate outcome of successful translation of new technologies and creation of value will have to be measured based on the gross revenues of new businesses catalyzed by the hub.

We can look at a few important milestones to defined success criteria for the hub over the next 5-10 years,

a. Translation objective (via Venture studio) - 30 startups with possible one startup reaching valuation in excess of $100mn in 5 years
b. Talent objectives - 550+ specialized talent creation in the hub’s core areas
c. IP & Technology frameworks - One core IP stack and technology ownership in critical area of telerobotics and next generation communication
d. Impact objective - Impacting 500mn people via products, companies, IP and open source

16. Evaluation

All the hub sponsored projects will be reviewed on a quarterly basis, with a major review on an annual basis.

The progress of the hub in its entirety, will be reviewed internally by the Hub Governing board, on a yearly basis. In addition, a periodic review by DST's Apex committee and other partners will be done.

17. Appendix A: Facilities

Robotics and Autonomous Vehicles research will need state of the art facilities to support technology innovation and research. In addition to supporting research and exploration, the laboratory facilities also enable hands-on training of manpower to get expertise in this very important emerging field. Towards this end, we plan to have a four tier facility:

a) Robotics laboratory - the Makery: This space will house smaller robots, associated instrumentation as well as tools and gadgets to make our own prototype robots and systems. It will be housed in the Robert Bosch Center for Cyber Physical Systems,
b) Drone testbed - the Dronery: This testbed will consist of a wind-shaping facility and an indoor drone testing space. This will be housed in IISc's airfield,
c) Mini Testtrack Facility: This will consist of a small outdoor test track to test autonomous (and semi-autonomous) vehicles (also enabling mimicking of indoor settings), with a next gen wireless infrastructure. This will be housed in IISc's airfield, and
d) Large testtrack and drone flight corridors: This facility will allow outdoor testing of unmanned air vehicles (microdrone size) as well as a multi-terrain ground test track to test autonomous and connected vehicles in outdoor settings. This will be setup in IISc's challekere campus.

These facilities will be available for free to all IISc faculty, collaborating faculty from partnering academic institutions and founding industry members of the consortium.

The facilities will be made available on a chargeable basis to all others.

We will next give more details on each of these facilities.

17.1. The Makery - Robotics Lab

Item	**Min. Qty**	**Description**	**Possible Vendors**	**Estimated Cost (INRLakhs)**
6DOF Collaborative Arm	2	Arm for collaborative robotics	DENSO, ABB, Kuka, UR	60
6DOF Industrial Arm	2	Normal industrial robot arm	Systemantics, Yaskawa, Dobot	30
3DOF Mini Arm	4	Desk top model	Systemantics, Dobot	10
3D Printers	2	High end 3D printer	Ultimaker etc	30
Consumables	NA	Motors, Drives, Actuators	Different Sources	100
VR Kit	2	Virtual Reality Kit	HTC, Oculus	10
AR Kit	2	Augmented Reality Kit	Atheer	20
Humanoid Robot	1	Humanoid Robot with Facial Emotion Engine	Hanson Robotics	60
Small Humanoid Robots	2	Smaller humanoid robots	Nao	25

Small Mobile Bots	10	Small indoor ground vehicles	Turtle Bots etc	50
Minibots		Miniaturized mobile bot kits	TI etc	15
Sensors (Lidars, mm-wave radars, Stereo cameras)	NA	Sensors of various kinds to be mounted on vehicles, as well as embedded in infrastructure	Different Sources	200
Total				**610**

Recurring costs (Power, Maintenance, Repairs, Warranties): 15L/year

17.2. The Dronery - Small-Scale Air Vehicle Test Facility

Scope: To build an autonomous unmanned aerial test facility. In a nutshell, the focus will be on the following:

a) Build a wind shape facility with Rain and smoke simulator
b) Drone park for testing the cooperative/swarm behavior

Background: Recent challenges of operation by the military in a complex environment and natural disaster management system world-wide motivated the researchers to build autonomous systems for operations in a complex environment like a forest fire, earthquake, rain and constrained spaces like a tunnel. Operating an autonomous UAV in this environment is challenging due to the absence of a reproducible environment for validation of the system. Further, emulating the worst-case scenario for flight worthiness is not possible. One can overcome above-mentioned problems, if we can recreate the environment in a confined space. Towards this, the project aims to build a unique wind test facility to generate any cross-wind, gust, urban canyon flow to validate the capabilities of UAV. Further, the facility also has smoke and rain simulators to create the real reproducible environment.

Development of Testing Environment

The biggest challenges in autonomous UAV and swarm technologies is a validation of the solution in the real environment. Innovative testing facilities are required to collect the data and validate the results for translational research. Further, such a test environment provides representative data for most of the urban operational problems. Also, note that collecting data outdoors is really hard or even impossible to collect due to the uncontrollable environment.

Windshape Facility and an Enclosed Drone Gym

This facility will have a WindShape [1] to allow us to validate the algorithm and reproduce the outdoor weather in a reproducible manner. The windshape is a modular and scalable system. Each module consists of 9 wind pixels and one can stack these modules to produce a wind wall of the desired coverage area. It is also possible to generate a trajectory of wind by arranging the modules in a curved wall structure. This will help in changing the direction of the wind and orientation of trajectories. Windshape will also generate Gust wind, shear, urban canyon flows to test every possible scenarios in an outdoor environment.

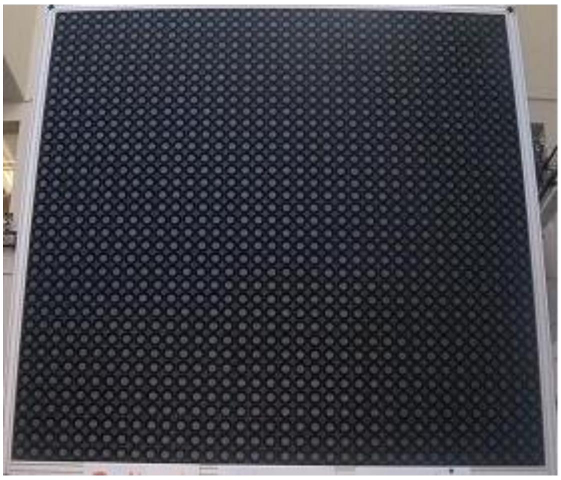
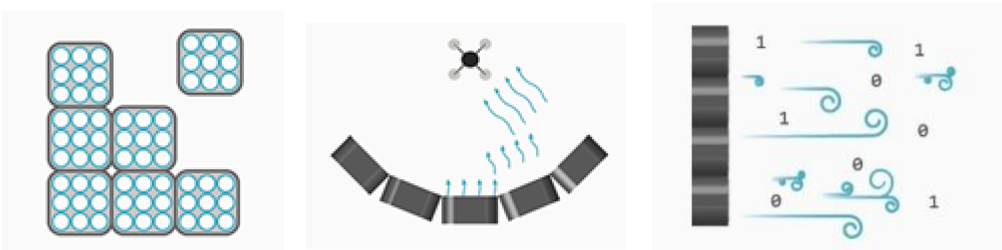


Figure 1. Typical WindShape Structure,with a 2D-array of controllable fans

Today, gathering in-flight data is a nightmare mostly because the tests are run outdoor, in an environment that cannot be controlled. It means tests are not reproducible and data are hard or even impossible to collect. The facility will allow your flyers to be tested 24/7 in reproducible and custom flying conditions.

The windshape construction is modular (as shown in Fig. 2(a)) and hence flexible to expand to accommodate bigger vehicle testing. Further, it is possible to control a certain fan and turn off other fans. Thereby, one can generate specific wind patterns and trajectory of wind for validation of vehicle behavior. Since each fan is controlled by a computer, it is possible to generate gust, shear, or urban canyon flow to verify the stability and maneuverability of the vehicle with high reliability.



(a) Modularity (b) Directional (c) Controllable

Figure 2: Windshape Modules

The facility also encompasses the drone park with an accurate tracking system for testing and validation of cooperative/swarm systems.

Space Requirement

The windshape experimental setup is 3m x 3m and requires a power of 144 KW with a maximum current of 450A. The setup can produce a minimum wind of 2m/s to 14m/s. In order to test the vertical wind profile, we need to tilt the setup, which requires a footprint of 3m x 3m. Hence, the lab space required for testing multiple drones is 12m x 30 m x 8m (W X L X H). Since the multiple-fans in the setup are completely computer controlled, we need to have a small server room with air-conditioning (only used during the experiments). The facility also houses the drone park for conducting experiments using cooperative UAV. The space of 8m x 15 m (W x L) will be used for tracking the drones accurately. The typical space requirement and location drawing is shown below.

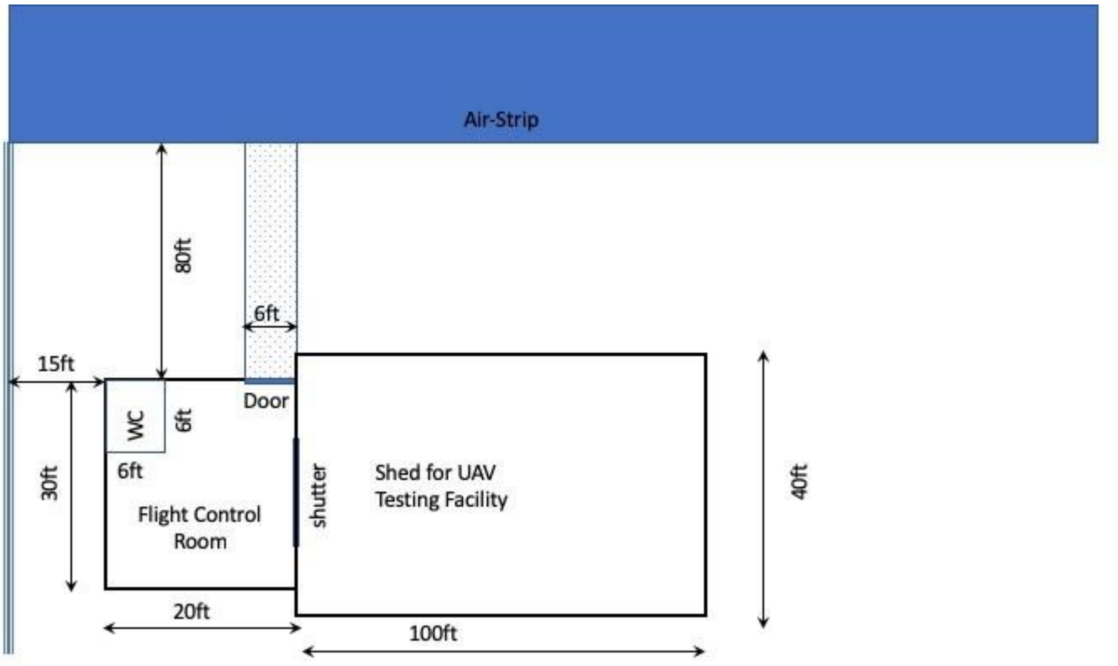


Figure 3. Space requirement for building drone park and testing facility

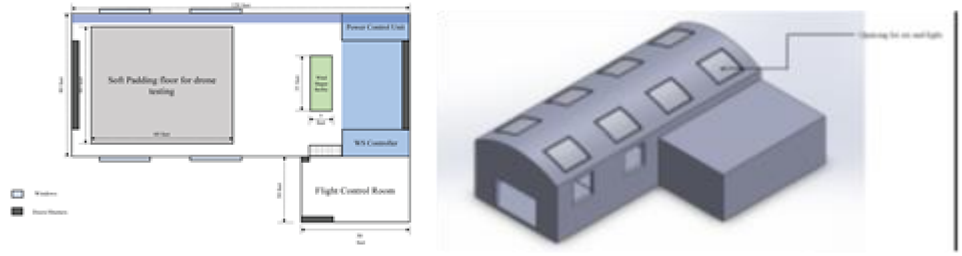


Figure 4: Schematics of the facility

Costing

Item	Description	Cost (INR Lakhs)
Windshape Modules	Fan array modules	200
Power Supply	Power supply Units	60
Control units & Software	Control of Fan modules and associated software	40
Civil Infrastructure	Shed, Nets, other ancillaries	70
MoCAP system	Tracking of drones	70
Total		**440**

Recurring costs (Power, Maintenance, Manpower): 10L/year

17.3. Mini Testtrack Facility

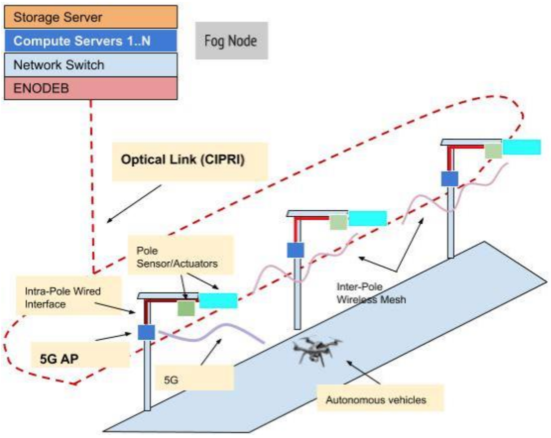


Figure 5: a) IISc airfield for mini testtrack b) Schematic of smart poles providing next-gen wireless.

The IISc airfield will be used to create a mini test-track. Figure 5a) shows the satellite image of the area. The aim of the testtrack will be to test small ground vehicles in low speed settings (suitable for indoor warehousing, factory mobility, on-campus mobility) type of applications. The entire region will be surrounded by smart poles that will deliver next-gen wireless facilities (5G and WiFi6). A schematic of the same is shown in Figure 5b.

This controlled environment will allow us to test realistic scenarios a remotely driven (or fully autonomous) vehicle may encounter in practice:

1. Lane discipline: Follow the marked lane and change lanes safely.

2. Speed Limits: Stay within the specified speed limit

3. Blind Spots: Acute turns, objects in vehicle’s blind-spot

4. Test remote drive system’s agility: Follow a specific route/designated pattern

6. Humans crossing the road

7. Other vehicles: Navigate, follow, overtake other vehicles

10. Communication blind spots and handovers

Costing

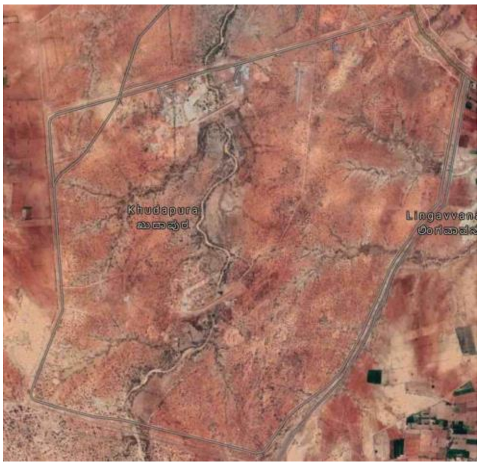
Item	**Description**	**Cost (INR Lakh)**
Civil Cost	Installation of poles, creation of test track	15
Next Gen Wireless Equipment	5G and WiFi6	150
Electronically Controllable Vehicles	Software/Electronically controllable vehicles - small and medium size	50

Sensors for localization and tracking	Radar, Stereo Cameras, Lidar,etc	100
Total		**315**

Recurring costs (Power, Maintenance, Manpower): 15L/year

17.4. Large Test Track and Drone Corridor Facility

A key enabling objective is to create a large outdoor robotics and autonomous vehicle test facility, in IISc's second campus in Challakere (~1500Acres) (Figure 6), that can also become a national resource for experimental research leading to certification for both drones and autonomous ground vehicles.



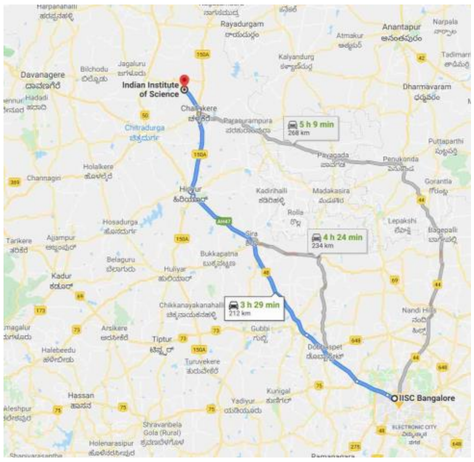


Figure 6:a)IISc's Challakere campus b) Location

Almost the whole area will be used for drone testing. One or more cell towers equipped with radars and communication equipment will be set up to develop and test out various concepts related to drone corridors, rogue drone detection, tracking & neutralization.

A schematic of the test drone corridor that will be set up in this facility and its various important components are given in Figure 7.

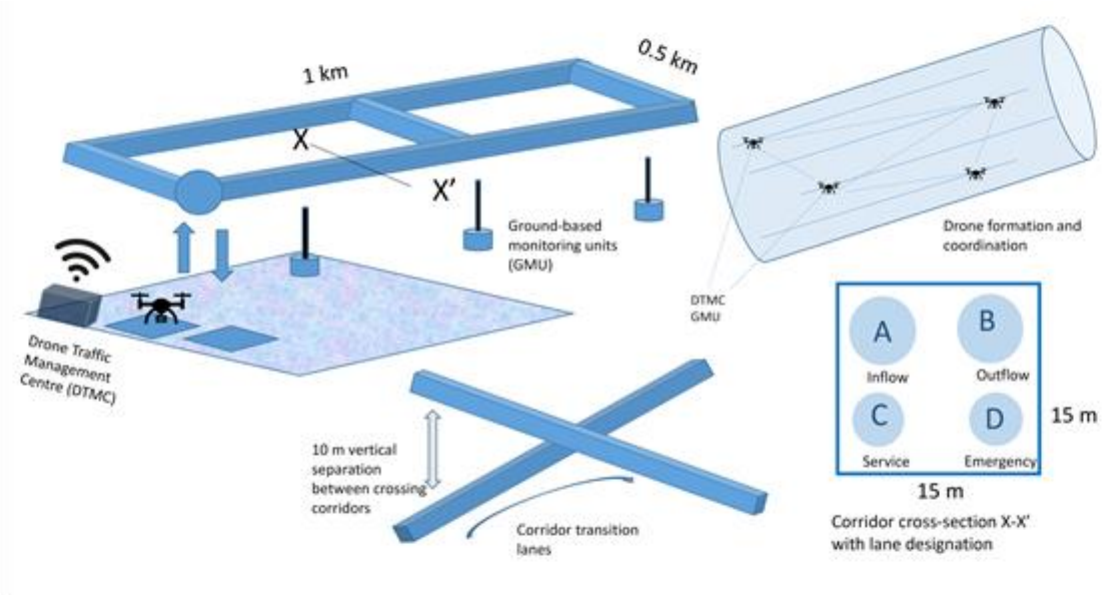


Figure 7: Pilot Drone Corridor Network.

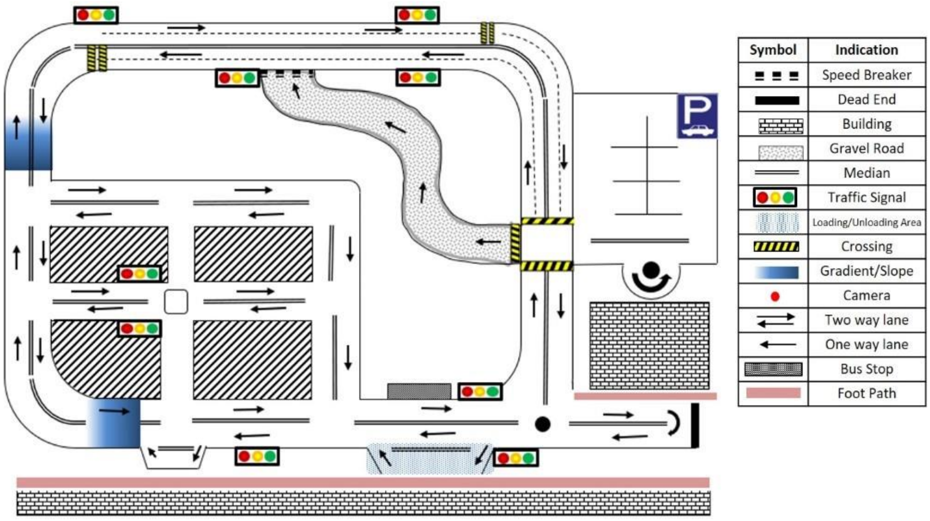


Figure 5: Road test-track

The objective of the road-circuit test track is to evaluate the autonomous capabilities of vehicles operating in various road conditions and understand the reliability of the solution. The typical test circuit planned on our campus is shown in Figure 5. It will be roughly 1km by 0.5km. The facility has a long stretch of road to test platooning and intersection with/with-out infrastructure to evaluate the V2V and V2I co-operations. Further, the circuit provides various road conditions, types of roads, parking, bus bay and loading/unloading bay. Using the facility, we will aim to validate the technologies developed to operate level-4 autonomous vehicles, test and validate their capabilities, collect information from various performance tests and generate scenarios for design, development and benchmark autonomous vehicle technologies. This will result in standards for certification of autonomous vehicles.

Costing

Item	**Description**	**Cost (INR Lakh)**
Civil Work	Setup road test track and other supporting infrastructure	100
Radar, tracking and signalling, Scada, AR/VR, HCI equipment	Track drones and vehicles, Human computer interface	200
Next Gen Wireless Equipment	5G and wifi6	200
Maintenance Garage	State of the art equipment maintenance facility	100
Simulation Framework	Software and compute infrastructure	100
Air Vehicles	Micro, Medium and Large Sized Air Vehicles	200

Ground Vehicles	Small, Medium and Large sized ground vehicles	300
Total		**1200**

Recurring Cost (Maintenance, Repairs, Warranties): 50L/year

18. Appendix B: Data Setu: a framework and facility for privacy preserving data hosting, sharing and analytics

18.1. Context

The covid pandemic has brought out the value of data, especially from diverse but interrelated sources, that need to be combined to effectively manage the response to the pandemic. Data from citizen apps (like Aarogya Setu), diagnostic clinics (for test reports), field agents (for contact tracing), line lists (from state health departments), mobility patterns (from telcos), hospital capacities (from private and public hospitals) and various other data items are needed to get a holistic view of the ground situation and the ability to handle it efficiently and effectively.

However for effective data analysis, we need the following technologies:

a) A privacy and provenance aware data collection layer that will allow crowd sourced and sensor data to be collected and made available for analysis, with full cognizance and control by the owner of the data
b) Data lake infrastructure allowing both encrypted and unencrypted data to be collected and made available for further processing
c) Secure compute infrastructure (along with open compute), to allow for analytics to be done on data
d) Rich, high quality data sets including GIS and other public data

18.2. Data Setu Facility

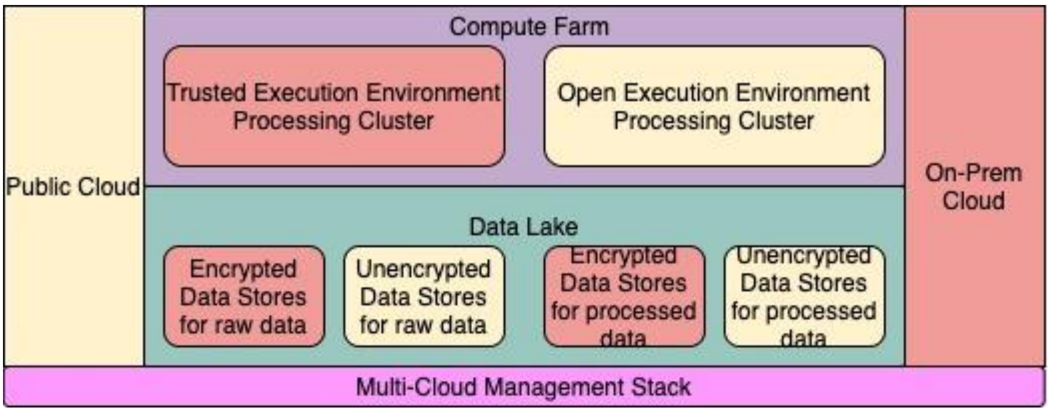


Figure 1. *Data Setu facility will be a hybrid-cloud setup consisting of data lake and compute infrastructure seamlessly operating across On-Prem and Public Clouds. Both encrypted and unencrypted data stores will be available. Compute infrastructure will consist of trusted and open execution environment clusters.*

Our proposed facility will be on a hybrid model - with an on-prem cloud setup within IISc and a public cloud in one (or more) of the cloud service providers. The facility will have a data lake and a compute farm. The data lake will have data stores for encrypted as well as unencrypted data. The compute farm will have compute clusters supporting a trusted execution environment as well as regular open clusters. A multi-cloud management stack will seamlessly manage data and compute across the two and will be built on open source technologies. The compute farm will have both non-GPU, GPU and HPC capabilities.

18.3. Proposed Technology Innovation/Development Projects

We plan to undertake the following technology innovation projects in synergy with this facility creation

18.3.1. Privacy & Provenance Layer (PPL) for Data Collection

We will develop an open source privacy and provenance layer that can be used across a variety of data collection devices like phones, IoT devices etc to allow for secure and privacy preserving data collection capability. This layer will be a library layer, built on TLS and other well established security standards and will be useful to application developers to build data collection applications. The layer will allow establishing trust in the hardware and its various components (like sensors etc.), firmware and software. In addition, when interacting with humans, the identity of the human will also be established (using existing identity management frameworks). The data, so collected, will be exclusively controlled by the data owner, who can determine whom to share it with. This is especially useful for data collected via smartphone apps - as the smartphone user then will have the ability to control access to their data. This layer will also support implementing differential privacy and other distributed privacy mechanisms.

18.3.2. Data Catalog

A data catalog holds meta information describing and adding semantics to the data sets and makes the data more valuable and useful to end consumers. The data catalog can also contain other information about the data sets - like user reviews, pricing, restrictions, licensing etc. However creating and maintaining data catalogs is challenging and we will explore automated ways for doing so. A version of the data catalog is available at https://datasetu.org

18.3.3. Authorization & Fiduciary

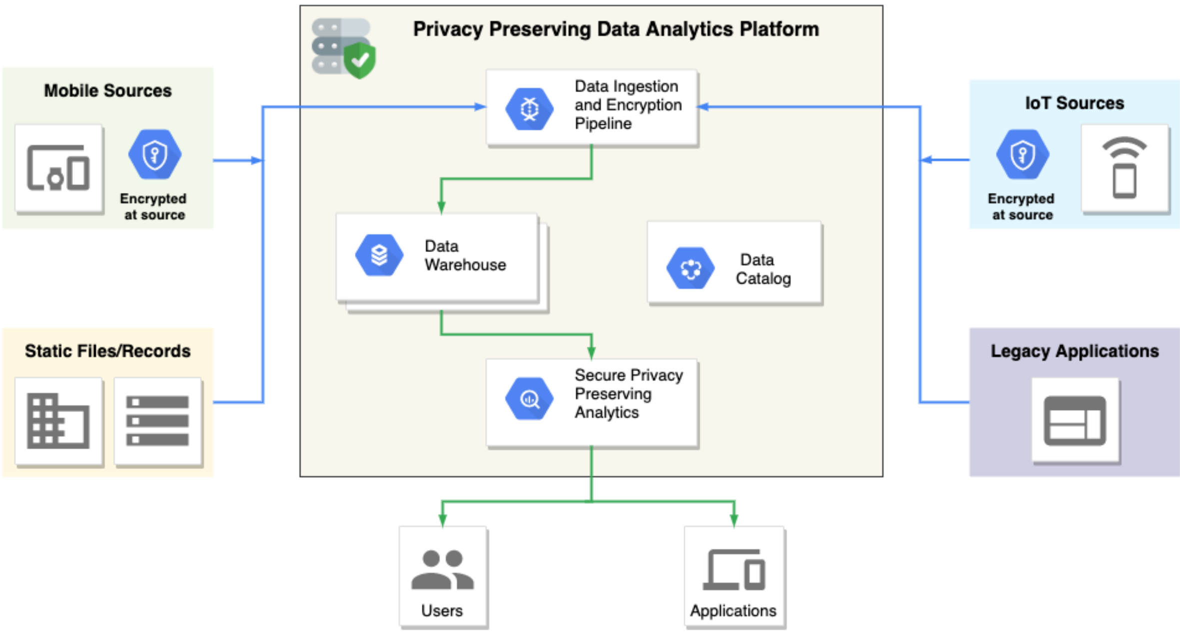
Data setu will enable data fiduciaries to host and manage data on behalf of their clients - who are the data publishers. It will provide mechanisms through REST APIs for the publisher to manage consent of their data. This allows the publisher to automate consent that controls "who" can access "what data", for "how long", at "what time", from "which locations'', and "how many times a day". This will be integrated with payment gateways to allow publishers to monetize their data. Dataset will provide this capability to all data publishers regardless of their size (including individuals contributing/publishing their data).

Data setu will allow publishers to classify their data using the following policy labels: (1) Public, (2) Protected, (3) Private, and (4) Confidential. Based on the above policy label, data setu defines the following policies associated with data: (1) Nature of data Information, (2) Authorization protocols and policy, (3) Consent, (4) Data locality, (5) Data retention, (6) Data storage, (7) Data usage, (8) Data audit, and (9) Data monetization.

18.3.4. Multi-Cloud Management Stack

We will bring together open source tools to manage data and compute in the hybrid cloud.

18.3.5. Privacy preserving analytics



A high-level view of the privacy-preserving data analytics platform is shown in the figure above. The testbed will cater to a variety of data sharing models. The data itself can be time-series IoT data, static files and records from government offices, data from mobile sources, data from legacy applications and so on.

The sharing models include:

- Free to use raw public data
- Free to use raw secure data
- Restricted access to raw secure data
- Restricted access to run authorized functions on secure data
- Restricted access to run authorized functions on secure data in the publisher's domain.

Bureau of Industrial Standards, Govt. of India is developing a data exchange reference architecture to (i) Discover, (ii) Share, and (iii) Access data; from various systems in smart cities as part of the "Smart Cities Mission". Data setu work will build on this.

Data is ingested from various sources such as IoT sources, Mobile sources, static files and legacy applications. The ingested data is encrypted and stored in the data warehouse. Data from mobile and IoT sources could be encrypted at the source. The existence of these data sources is catalogued for easy discovery and access. Free to use data of any kind can be directly accessed. Access to other types of data is strictly scrutinised through the use of data policies and/or certification of binaries that run on top of the secure data.

A Certificate Authority (CA) will be set up specifically for authorising applications under existing or new policies regularly. It will conduct appropriate manual and/or automated checks to ensure that the applications adopt privacy best practices and do not consume or reveal more data than required. After appropriate analysis, the CA shall generate a signed application binary along with a certificate. Signed applications can be deployed in a secure computing environment hosting the privacy-preserving analytics platform. The secure computing environment shall authenticate each application (using the CA root certificate). Applications that have not been signed by the CA or have invalid/expired certificates shall not be allowed to execute. The platform shall record all authorisation decisions in a tamper-proof log, along with additional metadata describing the set of data sources that the application will access and the entities that shall receive the results of the computation

Many of the components (such as Trusted Execution Environments, federated learning frameworks, public blockchains etc.) required to implement this platform with strong security guarantees already exist. The privacy-preserving platform itself requires implementation effort, which may vary depending on the kind of applications that need to be supported. Finally, a CA must be set up with members who are qualified to assess and authorize applications along with a secure PKI infrastructure. An initial secure cloud will be set up first using existing well-known technologies, to get the first set of analytics going. More sophisticated features, related to multi-party analytics, data marketplace etc., will be developed in consultation with the various stakeholders, subsequently.

We review some of the current approaches and supporting tools that are available.

Approaches:

1. VC3 is a system which uses SGX in the cloud that allows users to run distributed MapReduce computations while keeping their code and data private.
2. Graviton is an architecture for supporting Trusted Execution Environment (TEE) on GPUs
3. StreamBox-TZ is a secure stream analytics at the edge using TrustZone that claims to offer strong data security, verifiable results, and good performance.

Tools:

1. Asylo: Asylo (asylo.io) is an open framework for enclave applications
2. Graphene: Graphene is a Library OS (like a unikernel) for making Intel SGX integration easy.
3. Enarx: Enarx is a deployment system to enable running applications within TEEs.

Services:

1. Microsoft's Azure confidential computing aims at protecting data that is in use from malicious insiders who have administrative privileges or direct access. This is achieved running analytics in a Trusted Execution Environment (TEE).

Comparison of various privacy implementation techniques:

Approach	**Lossy?**	**Complexity**	**Maturity**
Minimization	N/A	Low	High
Redaction	Yes	Low	High
Aggregation	Yes	Low	High
k-anonymity	Yes	Medium	Medium
Tokenization	No	Low	High
Format-Preserving Encryption	No	Medium	Medium
Differential Privacy	Yes	Medium	Medium
Synthetic Data	Yes	Medium	High
Secure Enclaves	No	High	Medium
Mix Networks	No	High	Low
Multiparty	No	High	Low

Computation			
Partially Homomorphic Encryption	No	Medium	Medium
Fully Homomorphic Encryption	No	High	Low
Verifiable Computation	No	High	Low

Source: [Privacy Tools for Data Sharing]

18.3.6. Open Data Sets

Various critical data sets for smart cities, robotics and autonomous navigation will be collected and made available through this facility. These will include: Maps, Annotated and raw video, speech, text feeds for robots, Lidar/Stereo images etc. In addition, anonymized data sets from various participating government departments and private sector entities will be made available.

Costing

Item	Description	Cost(INR Lakhs)
On-Prem Compute and Storage	GPU, CPU, NAS, NetworkEquipment, High Speed Leased Line	100
Data set creation for Maps	high definition maps	250
Data set creation for Robotics	Video, Audio, Demonstrations	50
Data set creation for Navigation	Indoor and outdoor driving and navigation for vehicles	100
Total		**500**

Recurring costs (maintenance, warranty repairs etc): 10L/year

We will have a mix of on prem private Cloud+off-prem public cloud. Data storage and big data analytics platforms should be collocated.

For on-prem, we will have a SAN with 512TB eventual storage capacity, optionally a 1PB of tape storage for archival, a 24 to 48-node Big Data/HDFS cluster for on-site large-scale analytics, a 8-node containerised cluster for hosting production web servers for serving data, two DGX GPU systems for deep learning, and two big memory (1TB) machines. These will be ramped up gradually so that HW does not lie idle.

In addition, we will have seamless access to one of the public Clouds to provision VMs, move data, etc. based on project requirements.

19. Appendix C: Drone Skyways

19.1. Executive Summary

We will develop technologies for urban drone corridor networks and demonstrate via a pilot in a smart city, with an aim to support delivery of goods. Setting up low altitude drone corridors over class G airspace, will unlock enormous economic value, but presents serious technology challenges. These involve design of flight protocols for autonomous and BVLOS flight, geometry of the drone corridors in terms of dimension and lane distribution, lane change corridors, spatial and temporal distribution of the flight trajectory through the corridors, monitoring the progress of the flight, ensuring privacy, safety and security, fault recovery, identification, tracking and neutralization of rogue drones, corridor compliant drone design, V2V and V2X communication, design of take-off and landing chutes. We will address all these questions with our work culminating in a standards based Unmanned Drone Traffic Management (UTM) built on top of MoCA's Digital Sky platform and demonstrated in both our testbed and in a smart city.

19.2. Context and Goals

Unmanned Aerial Systems are expected to become the backbone for movement of lighter weight goods and materials across intra- and inter-city distances through the presently uncontrolled (Class G) airspace. The materials movement could be as diverse as harvested human organs for transplantation, to medicines and emergency supplies to less critical, but commercially attractive, goods like merchandise and food orders. However, any such movement at present is confined to a single delivery vehicle that flies through a designated large uncluttered airspace. As the traffic for this class of vehicles increases (as it is bound to, according to a recent FAA report that predicts annual growth rates of more than 24%, leading to an anticipated 7 million plus drones flying over USA alone by 2020), it would be necessary to create regulated flight corridors over cities to ensure safe flight while simultaneously ensuring high volume of throughput. This is critical technology for India, given the congested traffic situation in most cities and the consequent drop in average vehicle speed on roads. Assigning drone flights through corridors provides a compatible and safe mode of transportation with a greater ease of integration with urban airspace and infrastructure. Separate lanes for traffic direction also present limited inter-vehicle collision possibilities which can be overcome utilizing rudimentary sensor information.

However, setting up such low altitude drone corridors presents serious technology challenges that need to be addressed in order to design and develop a Drone Traffic Management Centre (DTMC), design of flight protocols, autonomous flight, geometry of the drone corridors in terms of dimension and lane distribution, lane change corridors, spatial and temporal distribution of the flight trajectory through the corridors, monitoring the progress of the flight, ensuring privacy, safety and security, fault recovery, identification of unauthorized drone access, corridor compliant drone design, drone sensor suits, V2V and V2X communication, design of take-off and landing chutes, etc. However, none of these aspects are being addressed as an integrated system in any drone related projects in India. An important aspect of making this system viable is to create a cyber-physical test space where the complete drone corridor design and operation can be set up as an experimental facility and demonstrated for deployment on a much larger scale. We propose to set up such a facility in the 1500 acres second IISc campus in Challekere, in Chitradurga, Karnataka.

A third objective of the proposal related to drone operation is development of counter-drone technology which will detect and neutralize rogue drones in unguarded airspace around important installations. Radar and acoustic sensors are proposed to be used for detecting drones. Detection of hostile drones and guidance of interceptor drones to neutralize such drones using human eye-gaze tracking is also proposed to be developed. Finally, capture or neutralization of drones using our own drones carrying nets and other capture devices are also a part of this proposal.

The drone corridor will be initially set up as a set of drone lanes (inward flow, outward flow, service, and emergency) stacked in a 3-D formation that will enable access of the lanes from each of the other lanes. Formation strategy in 3-dimensional space needs to be designed that takes into account the spatial formation of multiple drones, wake and downwash effects, and constraints on the delivery and take-off platforms. Access to emergency lanes through transfer chutes, and the points where the direction of flight changes, need to be designed separately as the typical dynamics of the drones require additional constraints on the lane change maneuver. Monitoring stations at periodic intervals will be used to ensure risk free drone flight through the corridors. Although the flight of the drones is autonomous in certain portions of the flight, it is still restricted by the constraints of corridors space allocated to it, and hence will have limited capability in terms of flight path change. This aspect plays an important role in designing collision avoidance maneuvers and will have an impact the drone specifications and capabilities that makes the drone “corridor compliant”.

19.3. Prior work

The drone team consists of members from IISc who have long experience in developing path planning, decision making, and detection algorithms specifically for drones. Some of these are the following: collision avoidance [Chakravarthy and Ghose. Lima et al.], drone path planning in 3-D space [Hota and Ghose], drones for carrying out complex tasks like fire fighting, intruder interception, building construction [www.mbzirc.com], drones for agriculture applications [Hegde and Ghose], Some of the specific works on drone maneuver planning include landing guidance methods for quad-rotor drones [Gautam et al.] , smooth path planning through annular passages [Upadhyay and Ratnoo], robot trajectory following [Chowdhury et al.], nonlinear control strategies [Chowdhury et al.] , vision based drone collision avoidance [Sumedh et al.] and drone surveillance system [Singh et al.]. On drone detection, notable works include position and orientation detection using ranging sensor [Chepuri et al.] and radar signal processing for range and velocity estimation [Tehodi et al.].

The works [Nostrand et al.] and [Motro et al.] address demand analysis for spatio-temporal distribution of vehicles and role of dedicated short-range communications (DSRC) for collision avoidance, respectively. Dynamic airspace utilization algorithms were presented in [Wong et al.] and [Venugopalan et al.] present sector based air traffic management principles. Relating to counter drone response and guidance [Prabhakar et al.] present interactive eye gaze based control of vehicles and using saccadic information for cognitive decision making is discussed in [Biswas and Prabhakar].

On security and privacy of drones [Vijeev et al.] present regulations and [Brasser et al.] discuss security policies with trusted hardware support.

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19.4. Research Activities

Formation strategy in 3-dimensional space needs to be designed that takes into account the spatial formation of multiple drones, wake and downwash effects, and constraints on the delivery and take-off platforms.

Drone coordination for motion through lanes and corridors involves developing new control methods for 2-D and 3-D drone platooning. Disturbance mitigation is a primary objective in autonomous vehicle platooning. There exist works on platooning for ground vehicles wherein the disturbances (by the very nature of a wheeled ground vehicle) are only in the direction of platoon motion. Prone to downwash and gust disturbances, platooning in drones presents a far more challenging scenario with disturbances of dynamic nature appearing from all possible directions, together with the limited control actuation authority. New trajectory planning methods would be developed for landing and take-off of drones which specifically incorporate the spatio-temporal constraints for multi-vehicle coordination. Design of safe emergency maneuver protocols for exiting a main traffic lane and re-coordination of platoon forms another challenging exercise.

Identification of rogue drones entering a dedicated drone corridor will be addressed using compliance communication handshakes using DTMC and GMS. Specific protocol development would focus on smooth operation under such disruptions. We will pursue this by building security and privacy policy enforcement mechanisms into the software stack of the drone, backed by trusted hardware on the drone to ensure robust compliance.

Robustness of regulated drone operation is an overriding and mandatory requirement and would need the use of modern stringent robustness enhancement techniques that would guarantee high level of safety under worst-case scenarios. The very nature of drone vehicle dynamics and its vulnerability to external disturbances makes this task critical and would benefit from multi-disciplinary approach involving control theory, vehicle design, AI, fault tolerant design, and robust decision-making.

19.5. Technology/Product Development

Creating regulated drone lanes or corridors with high robustness guarantees will involve development of several new technologies, specifications and standardizations related to the drone corridor design, communication and monitoring strategies, strategies for directed collision-free formation flight in confined airspace, semi-autonomous flight control and traffic management systems, and security and safety. We expect this development to happen not only at the algorithmic/software level but also at the actual operational level with actual drones. The “corridor compliance” requirement of COTS drones will need specification development and standardization as well as development of “corridor complaint autopilots” that could be integrated with COTS drones to make them fully corridor compliant.

The technology developed under this focussed activity will not only produce a formalized framework for establishing and operating drone corridors, but also give rise to fundamental new technology that can be used and commercialized for many other important applications like aerial agri-robotics, disaster management, defence technology, development of new drones, etc., which would have enormous impact on the growth of drone industry in India. We also expect that these developments will naturally lead to IP creation, patenting opportunities, licensed technology development, vehicle and operating specifications, and standardization development in this new area.

19.6. Collaboration

In drone space there are several groups of young and active faculty in academic/research institutes working on developing new autonomous and semi-autonomous drone technologies in India. We have contacted many of them and received support and agreement to be collaborative partners for this proposal from IIT Kanpur, IIT Bombay, IIT Madras, IIT Kharagpur, and IIT Jodhpur. Among industry partners we have been working closely with Intel India and Tata Consultancy Services on drone related projects. IISc and TCS are jointly partnering to take part in the prestigious MBZIRC International Robotics Challenge [www.mbzirc.com] where drones are critical components in achieving some of the most gruelling tasks of intruder capture, building construction, and fire fighting using autonomous and coordinated drone-UGV systems. Intel and TCS have both agreed to partner with us on this proposal. We are also in the process of discussing with DRDO and its labs to be a part of this venture and we are confident of getting them on-board too in the development of critical drone related technologies.

We will also work closely with the Digital Sky Platform team and the Ministry of Civil Aviation to connect closely with India’s ongoing regulatory activities in the Drone space.

Internationally, we have reached out to drone technology researchers in academia and industry and have received their consent to be our partners. Texas A&M, Univ. of Texas-Arlington, Missouri

University of Science and Technology, University of California - Los Angeles, and Nanyang Technological University are some of them. We are discussing with NASA researchers, who were primarily responsible for designing the initial blueprint for the UTM in the USA, and we hope to get them as a part of our advisory body.

20. Appendix D: Technologies for Autonomous Ground Vehicles

AI powered Autonomous Vehicle

Executive Summary

As the world gears up for the Industrial revolution 4.0, it is imperative that India develops an advanced Autonomous Ground Vehicle (AGV) capability indigenously. With AI, IOT and 5G communications as key enablers, the focus is essentially on building a Level-4 autonomy for ground vehicles, operating in an unstructured environment. For sustainable growth, a knowledge-based economy like India requires various social and industrial sectors to develop at a healthy pace. Transportation sector is vital for public and logistic operations, and AGVs can contribute greatly to enhancing efficiency and safety of these operations. In addition to these, autonomous ground vehicle opens a new opportunity in rescue mission, defense and in space exploration.

Specific Goals

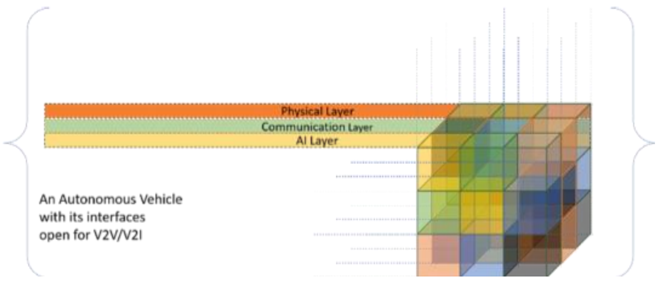
Our long-term objective is to develop technologies (both hardware and software) for fleets of autonomous vehicles operating at Level-4 autonomy in an unstructured but restricted environment (low vehicular movement and moderate human activity). This objective comprises two major aspects (a) vehicle automation and (b) mobility on demand. To achieve this goal, we need to address several research/technological challenges in topics such as artificial-intelligence-driven perception for scene understanding/situational awareness, advanced technologies in navigation, and control, intelligent transportation and mobility planning, vehicle-to-vehicle and vehicle-to-infrastructure interactions, cyber security, and resilient operating systems.

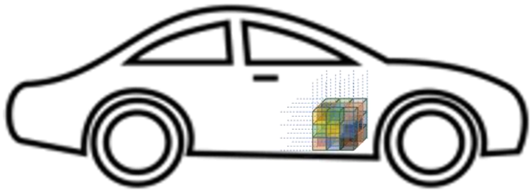
Technology development and translational road map is:

- Build an autonomous vehicle technology development testbed that incorporates advanced communication technologies, IoT enabled infrastructures, as well as a realistic driving environment aided by robotic avatars. The goals of this activity will be to:
    - Identify fundamental technologies required to operate, test and validate autonomous vehicles,
    - Collect datasets (including failure modes) from various performance tests so that they can help researchers to design, develop and benchmark autonomous vehicle technologies for different kinds of driving conditions, and
    - Provide results of analysis of test data to authorities in order to formulate minimum standards for certification of various functional aspects of autonomous vehicles.
- Demonstrate multi-point logistic operations by fleets of autonomous connected vehicles that perform at Level-4 autonomy in the testbed. Some key features are:
    - AI driven assistive systems to handle unexpected situations,
    - Navigation in adverse conditions such as uneven surfaces, GPS denied environments and low-resource situations,
    - Mobility-on-demand including, planning and decision making in the presence of non-cooperative vehicles, and
    - Interaction/cooperation with infrastructure and other vehicles for reliability and security.

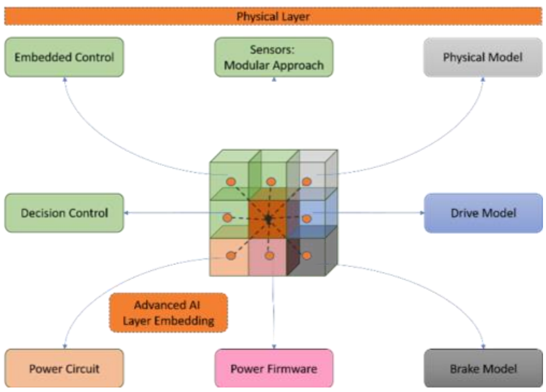
Overall System Architecture

At the core, an autonomous vehicle (AV) comprises of three layers (Physical, Communication, and AI) that are tightly coupled together which provides a seamless interaction with other AVs and Infrastructures (V2V and V2I). An AV could be a car, a taxi or a truck.

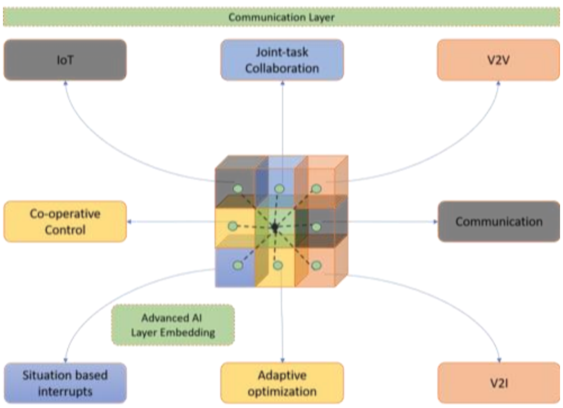




An AV’s interfaces interact with the core system all the time to achieve the Level-4 autonomy. Total control and semi-control is achieved through the Advanced AI – Layer Embedding, which focuses on privacy, agility, ethics, and safety as its primary goal.

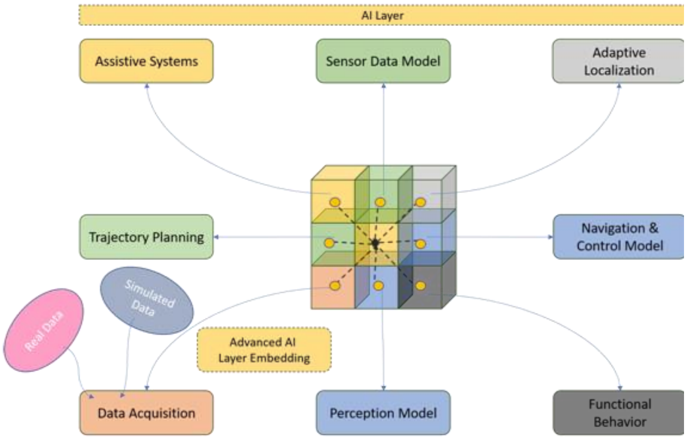


Physical Layer focuses mainly on the power electronics, on-board sensors, firmware, and control mechanism of an AV. The decision control acts as a bi-directional interface to the other layers. It constantly updates the Physical, Drive, and Brake models as it learns over time. It is only through this layer, the data is shared among other vehicles and infrastructures.



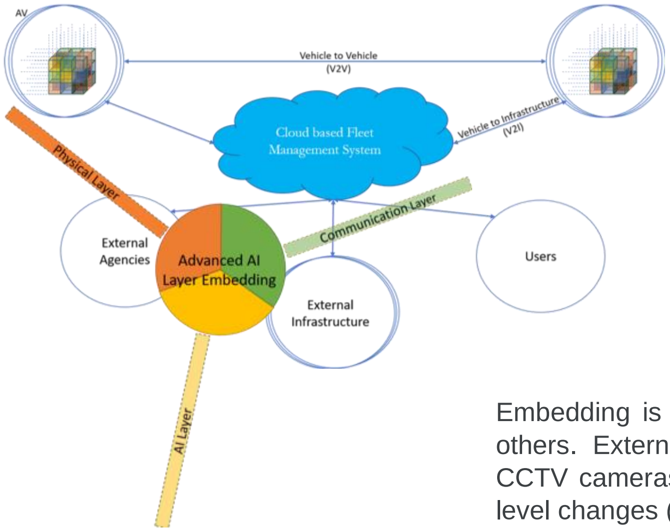
Communication Layer is the central part of the IoT (with Industry 4.0 stack). It exposes the data through state-of-the-art wireless channel and integrates various safety protocols. In general, an AV is advised to perform a task. But here, an AV can over-ride the primary task only when there is an ethical, safety or privacy concern. The co-operative control and joint-task collaborative control is a 24 hour workhorse which helps achieve the overall goal of Level-4 autonomy to its reality. The V2V, V2I and the communication outside the vehicular network is the primary goal.

AI Layer forms the most important part of this architecture. It employs various state-of-the-art machine learning architectures and indigenously developed algorithms. Trajectory planning, navigation & control and various other localization algorithms are integrated in this layer. The Assistive Systems and Perception Model forms an integral part. It uses the data (both simulated and real) that is acquired over time to provided various services including vehicle health monitoring, imagery, sensors, telemetry, behaviour modelling, task modelling, overrides (vehicle-level, user-level, and cloud-level). This layer



exposes the vehicular information through secured APIs that can be seamlessly integrated to various platforms including (existing taxi networks like Ola, policy-level networks, external agencies and infrastructures) over the cloud.

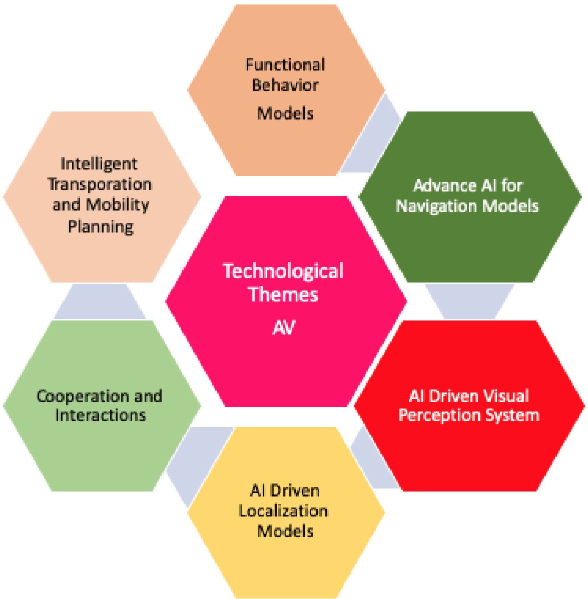
The Cloud-Based Fleet Management System is natively designed keeping in mind various challenges in India. The cloud facilitates productivity and infotainment with the help of customized WebRTC protocol. It supports both low-speed and high-speed networks with loss-less telemetry transmission across various channels.



Users are classified either as one-vehicle-user, many-vehicle-users, and cloud-maintainers. The external agencies can be Indian Government, insurance agencies, other Autonomous Vehicle companies or AI companies. One of the most important goals is to certify if an AV is suitable to Indian standards. The Advanced AI Layer Embedding is a novel addition to this architecture among others. External infrastructure are sensory channels like CCTV cameras, traffic signals, control rooms, other object level changes (people/vehicle/traffic-incidents/weather).

Technological Themes

The AGV test facility has a long stretch of road to test platooning and intersection with/with-out infrastructure to evaluate the V2V and V2I co-operations. Further, the circuit provides various road conditions, types of roads, parking, bus bay and loading/unloading bay. Using the facility, we will aim to validate the technologies developed to operate Level-4 autonomous vehicle, test and validate their capabilities, collect information from various performance tests and generate the scenario's for design, development and benchmark autonomous vehicle technologies. This will result in standards for certification of autonomous vehicles. The following are the proposed technological innovations and advancements:



Overall Technological Themes in AV

I. AI driven visual perception system for situation/environmental awareness:

- **Real-time video analytics:** We will develop techniques that will combine analytics over real-time video streams from the autonomous vehicle along with analytics over video from fixed cameras on campus to enhance situation and environmental awareness. These will then be used to undertake tasks such as detecting events (e.g. track objects or activities of interest) across the video network based on additional knowledge on the campus road network. Such information processed in real-time can also be used to plan missions for a fleet of autonomous vehicles, such as ensure proximity to events of interest and ensure spatio-temporal video coverage of specific regions of interest. One of the challenges is to combine the various video streams (from fixed as well as moving cameras) to generate a coherent spatio-temporal event map. These video inference techniques will be deployed both at the edge (on-board the AGV) as well as the private cloud, and closely work with 5G and other communication technologies to determine where and when to run what analytics.
- **Privacy-sensitive data management platform:** We will develop a privacy-sensitive data management platform that will collect, curate, annotate and manage multi-modal data on video and other on-board sensors of the AGV and its telemetry, odometry, and IMU (such as GPS, wheel encoder and accelerometer data) on a private cloud. This will allow annotation of data to help with classification, training of deep models, performing text-based queries over the collected data, and can be used for mission planning across the test-bed. A key aspect of this data platform is to ensure privacy policies to be natively enforced at the data platform level to ensure that portions of the multi-modal data that should be shared with specific researchers only will be made available.
- **Object Detection and Segmentation:** The objective of this work is to develop a state-of-the-art model for object detection and segmentation for Indian roads. There are some initiatives to collect driving data in Indian conditions [XX], which we can leverage to build models. However, since these datasets are not extensive, we would also like to use foreign data to develop models and then adapt them for the Indian scenario via domain adaptation techniques [xx]. Another aspect of this work is to detect objects or events of interest by combining Lidar or other sensor data with RGB data.
- **3D mapping from Lidar data:** the objective in this direction of research would be to obtain an accurate 3D scene of the vehicle path by fusing Lidar and other RGB camera data. In the past we have explored estimating depth map just from a single RGB image in an unsupervised setting. Now this will be extended to utilize the sparse Lidar data to achieve better accuracy. The 3D mapping detects various objects in front of the vehicle and provides accurate distance

from the vehicle. This enables the vehicle to find the optimal safe path towards destination point.

II. Advanced technology in navigation and control:

- Efficient trajectory planning: The focus is on developing efficient trajectory planning solutions for autonomous vehicles operating in an unstructured environment. Collision avoidance, local conflict resolution, and smooth path planning are primary objectives at the local path planning level. Path planning with limited and intermittent sensor information is another area of focus in this regard.
- Navigation algorithms for low-resource conditions: Course-grain navigation is relatively easy if GPS is available. In the absence of GPS the problem of navigation remains an important research question. We will initiate a comprehensive investigation of the problem of Autonomous Navigation in restricted (but unstructured) environments. We believe this scenario is challenging but also tractable enough to develop technologies which are at the level of TRL-6 or above in a 3 year time frame. There is a plethora of existing work in the areas of visual navigation and Lidar-based navigation. Visual navigation methods generally fail in case of fast-turning motion, outdoor (wooded) settings, and dynamic scene changes with moving objects. Lidar-based navigation generally works by creating a high-definition map and is expensive. Our goal is to develop Simultaneous Localization and Mapping (SLAM) algorithms which are at the heart of Autonomous Navigation of ground vehicles. The challenges envisaged are manifold, namely map creation, map update, map access in scenarios where cost is a factor and connectivity are intermittent. In each of these cases, we will strive to improve on the state of the art and demonstrate the utility of the developed algorithms on an actual autonomous vehicle navigating in the proposed test bed.

III. Intelligent transportation and mobility planning:

- Cloud based Fleet Management System
- AI for heterogeneous AV vehicle deployment for demand-supply management

  This should include problems related to multi-task planning, multi-vehicle path planning, multi-robot exploration, etc.

- Scenario based optimal control for demand satisfaction for multi-point Dial-A-Ride-Problem (DARP)
- Understanding User-Experience and Planning for larger deployments

IV. Cooperation and interaction:

- Optimal multimodal network leveraging complementarity of V2V and V2I: In recent years, DSRC (Wi-Fi based) and C-V2X (cellular) have emerged as the two technologies of preference for V2V and V2I communication. These two competing technologies provide capability to enable communication between vehicles and between vehicle and compute-rich control centre. This gives us an opportunity to setup a multimodal network that tries to optimally use the complementary benefits of V2V and V2I communication. Furthermore, many optimization frameworks are now available to learn optimal communication policies that are aware of the situation at hand. However, most of the past research has pursued these threads in isolation or in theory, and an end-to-end implementation with real application is missing. We will demonstrate a continuously optimizing network framework in the proposed test-bed. In particular, the goal is to develop a framework where communication performance can be optimized not only keeping in mind the low-level network state but also other high-level features such as location of the nodes and the joint-task collaborative task for which the nodes are communicating. Furthermore, we strive to enable an information exchange between the application layer and communication layer so that the high-level control and AI algorithms can do the planning, keeping in mind the state of the network. For further elaboration of the key challenges and proposed solution, please refer to the description of the horizontal components on AI and Control and Information and Communication Technologies.

Technology and Product Development

Technology:

- **Localization and mapping:** Low-cost SLAM (low resolution Lidar + vision, incorporating prior knowledge (e.g., about the map, topography, other structures) in learning, robust outdoor visual SLAM.
- **Situational awareness:** India-specific object detection and segmentation of video data (animals, thela-walahs), lidar-based object detection, scene understanding, human activity detection, event detection, adapting depth-from-mono to new unknown environments.
- **Exploration:** cooperative exploration, cooperative sensing (multi-sensor fusion, multi-vehicle map fusion, etc).
- **Movement planning:** motion planning in unstructured environments, (planning and decision making in non-cooperative situations), end-to-end learning of driving in unstructured environments.
- **Goal-oriented collaboration:** V2V and V2I based fleet navigation in dynamic environments, Infrastructure-aided navigation.

Products:

- **Hardware**: Kits for converting conventional vehicles to drive-by-wire, AI on the edge
- **Software**: Drive-by-wire to autonomous (including localization and mapping software for unstructured environments), plug-ins for various types of sensors to improve localization/mapping, AI-driven assistance (driver monitoring, automatic breaking based on event sensing, automatic parking, pose estimation for specific tasks such as pick-up), mobility-on-demand solutions.

21. Appendix E: Next Generation Tele-Robotics

AI Driven Supervised Operation of (Semi) Autonomous Machines

21.1. Executive Summary

Machinery used in various verticals like Agriculture, Mining, Warehouses, Hospitals, etc. are currently manually operated by a human operator sitting inside or in close physical contact with the machine. However, various considerations like environmental- or work-related hazards for the operator's health, labour costs for skilled operators, etc., brings out a need for tele-operation of these machines, with either semi-autonomous or fully autonomous capabilities.

Tele-operation technology has been around for long - however it has been used sparingly and only when direct human operation is infeasible (for e.g. Mars Rover or in hazardous sites).

In this program we will develop the technology stack for making robust tele-operation practically feasible. The technology stack will be easily customizable and deployed across many different verticals like farming, warehouses, healthcare, mobility and mining.

21.2. Context and Market needs

According to Tractica Research[39], the need to automate physical processes and merge it with the digital ecosystem is going to result in a $248.5 bn market by 2025, comprising Personal robots, Commercial robots, Industrial robots and Military robots.

1. The personal segment—robots used for entertainment, cleaning, education, security, and household applications.
2. The commercial segment—robots used for transportation (cars, UAVs and others), medical and surgical purposes, maintenance, agriculture, and construction, among other applications.
3. The industrial segment—robots used in applications such as welding, assembly, painting, and material handling. This segment is going to see a massive growth post covid.
4. The military segment—for unmanned aerial, ground, military exoskeletons, and underwater vehicles, among other applications.

Autonomous/Semi-Autonomous mobility of vehicles in warehouses, mines, ports, campuses, etc. has the potential of tremendous economic impact. These spaces are unstructured, yet restricted in terms of overall traffic and hence offer a possibility of development of robust solutions based on latest advances in Sensors and AI. In addition, air mobility of micro and mini air vehicles opens up new societal and business applications, while it has its own different set of technological and regulatory challenges.

Further from the technology research and translational roadmap perspective, we are looking at,

a. Teleoperation of robots (1-3 years) - By combining high speed and low latency communication (5G), we can enable robots to address the uncertainty in the environment by allowing human perspective and ability to monitor and manage the robot operation. The problems being addressed can range from tele presence to tele collaboration.
b. Teleoperation combined with limited autonomy (2-5 years) - By combining low latency communication with limited autonomy, i.e., in the shared control paradigm, quite a few tasks in consumer and commercial segments can be automated. Especially for a country like India, it will be a boon for enabling employment for people without the need for migrating to richer countries.
c. Fully autonomous robots (5-9years) - By leveraging full autonomy, we can enable complex social workflows and enriched behaviours. This can find deeper adoption in multiple markets from

[39] Robotics market forecasts : https://tractica.omdia.com/research/robotics-market-forecasts/

personal, commercial and military markets. However even in this segment, researchers are finding a need for tele-operation[40].

21.2.1. Technology Themes

Robotics provides great opportunities for innovations in Component Designs, Software, Electronics, Algorithms and finally Manufacturing. High quality but low cost motor design, their controllers, embedded real-time OS and middleware, formal techniques, low cost sensors for localization, perception, real-time multi-sensor fusion, secure hardware and software are some of the key areas, ripe for innovation. Tele or Supervised Robotics will be a crucial technology that will play an immense role in the future. These are already available in specialized domains like surgery[41]. But making these technologies low cost, versatile, and robust will enable mass deployment and open up new services industry for remote delivery of all kinds of skills and not just surgical skills.

Autonomous vehicles for land (both indoors and outdoors) and air (micro- and medium-sized) offer opportunities in innovation and manufacturing. Technologies for low cost sensors, infrastructure needed to support operations, tele operation and management, optimal utilization of next gen wireless, novel operation modes like platooning, swarming, exploration, etc., are some of the areas ripe for further innovation.

Learning and Control is a hot topic of research and innovation to enable these machines to work in complex unstructured and semi-structured environments. Complexities of the machine and its interactions with the environment - preclude classical approaches of control and need to use data driven approaches based on ML and AI. However, engineering these approaches to be reliable and explainable, incorporation of domain knowledge, and achieving the right balance between direct and supervisory control is an exciting challenge.

CPS Methods involving co-design and co-simulation of hybrid systems (digital-cyber portions along with the analog real-world environments), will be critical to successfully engineer these next generation robots, and will need innovations in new analysis, verification and testing techniques.

Vision and Sensors, both the hardware and the algorithms will be critical differentiators and enablers for these machines. From the hardware perspective, motors, mems, fibre optics, flexible sensors, micro-sensors, mm-wave, lidars, video and stereo, array microphones, etc. are some of the important technologies which offer interesting opportunities for innovation. Sensor fusion to achieve higher reliability, semantic scene interpretation and situational awareness are some software challenges.

Speech, Language and Human Interface will be essential to be able allow a larger number of the general population to interact, use and work with these robots. Speech and Language especially is the most important and promising as it can lead to a very natural and low cost way for humans to interact with these machines. At the same time, other modalities of Human-Machine Interfaces will also become extremely important areas to focus on.

Artificial General Intelligence where the robot is able to work and handle situations it has not been trained for, will become an essential requirement as they start getting deployed in ever more unstructured and uncontrolled settings. Being able to design behaviours where these machines can do “reasonable” things (i.e., simulating “common sense”) in unusual situations, will become a critical engineering requirement (analogous to exception handling in software design).

Next Gen Networks involving high bandwidth uploads and low latency reliable communications will provide a different paradigm for designing connected robots - where data, information and inference can be shared across heterogeneous machines in real-time to improve their operations. Hence we will no longer think of designing isolated machines - but connected machines which offers exciting and challenging opportunities for innovation in all aspects of their engineering.

[40] https://towardsdatascience.com/the-remote-control-phase-of-self-driving-cars-f3bbe5ee3e60
[41] https://www.intuitive.com/en-us

21.3. System Model and Components

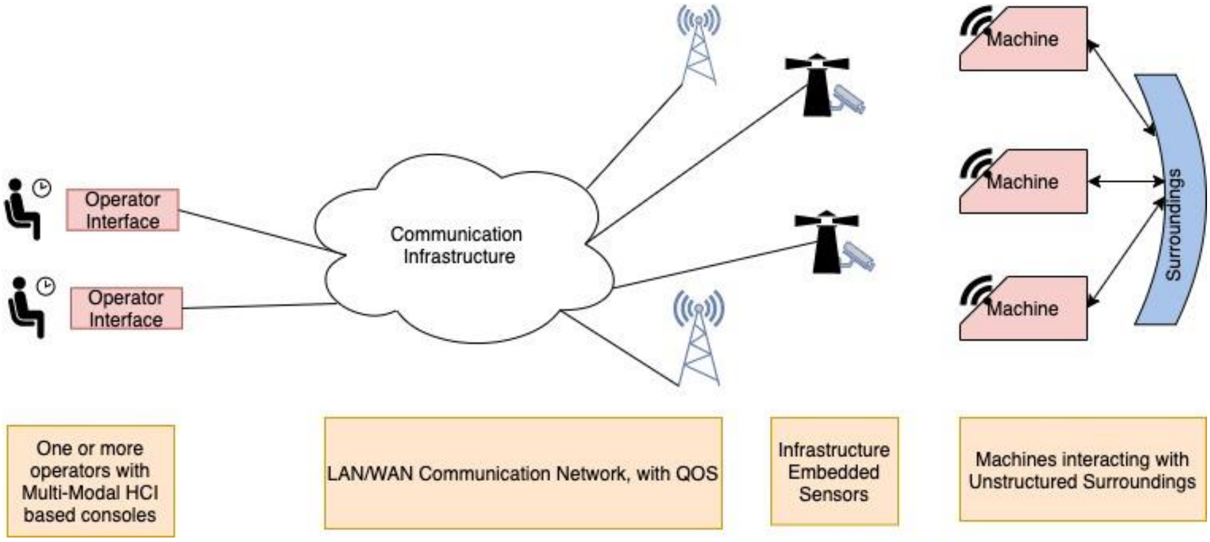


Figure 1: System model for Tele-Robotics

Figure 1 outlines the essential structure of a tele-operation system and involves:

- One or more remote machines, interacting with their local surroundings
- One or more human operators who supervise or control the machines
- A communication network that connects the two.

The machines interact with their surroundings, which are unstructured. However, we might have beacons or other sensors embedded in the infrastructure, to provide additional information to the machines and the operator, for safe and successful operations.

Data from the sensors in the machines may be locally processed and/or sent to the remote operator.

Operation decisions may be taken locally in the machine or by the human operator and are converted into actuation commands for the machines.

The communication network provides a certain quality of service to ensure the best possible communication channels.

The user-interface to the human operator, can take various forms depending on the granularity of interactions. It could be a simple display and keyboard, a joy stick, a speech interface or a full-blown virtual reality/augmented reality framework.

Depending on the sophistication and level of human control of the machine, a single operator might control a single machine or supervise operation of multiple autonomous machines.

Figure 2 outlines a few scenarios and use cases for tele-operation of machines.

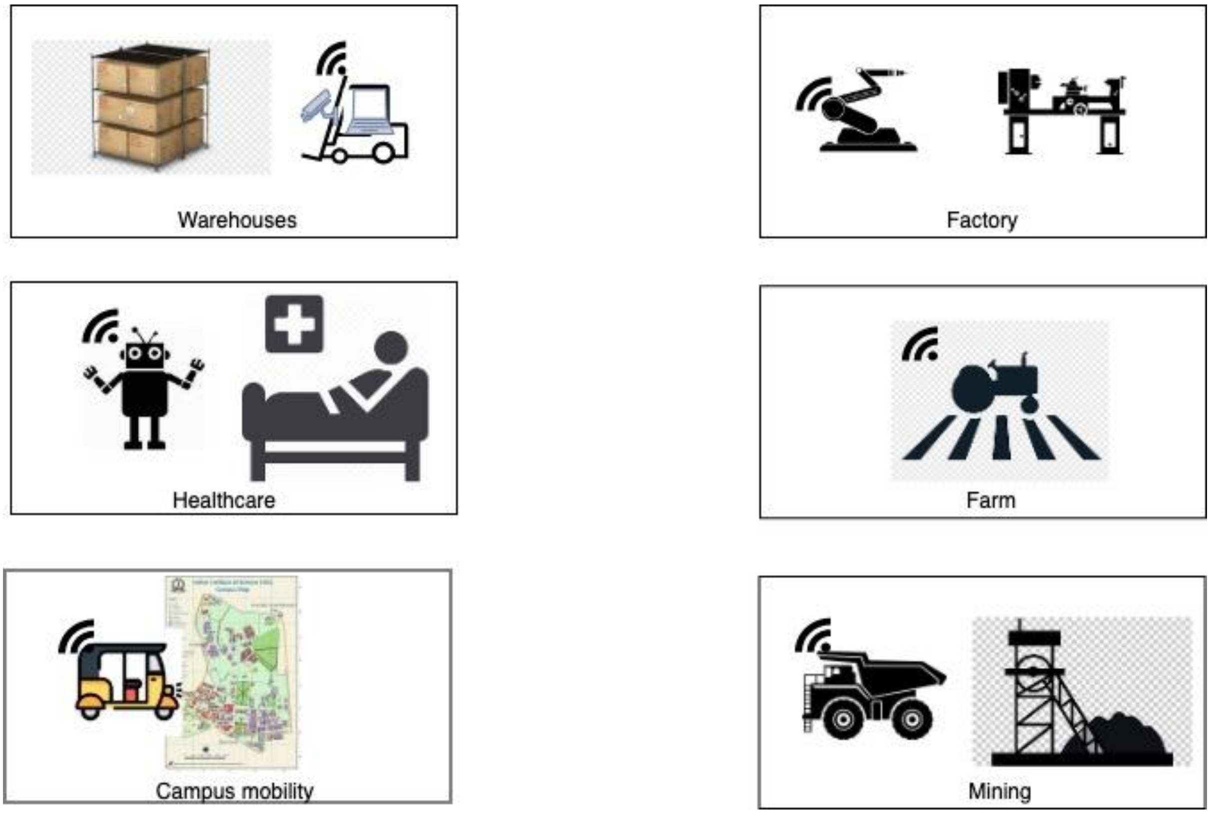


Figure 2: Use cases for tele-operation

Warehouses: to move items and supplies between various zones

***Factories*:** to enable operating various tools on the assembly lines

Healthcare: to provide care to patients

Farms: to perform various tasks like ploughing, harvesting, deweeding, etc.

Campus mobility: to operate driverless vehicles to ferry passengers and goods within a restricted environment

Mining: To ferry mined items out of the mines.

There are many more use cases, but above set brings out the universal set of problems, for most tele-robotics applications, namely:

- Mobility in unstructured and dynamic environments
- Localisation and mapping
- Perception and situational awareness
- Physical interaction with surrounding environment
- Social interaction with humans
- Safe behaviours under loss of connectivity
- Overall safe operations
- Supervision and interaction of the operator with the machine at as high a level of abstraction as feasible

The overall system has to be designed to be

a) reliable

b) robust to various failures

c) secure

d) responsive

e) efficient

f) maintainable

g) modular

h) safe

i) Extensible.

21.4. Software Architecture

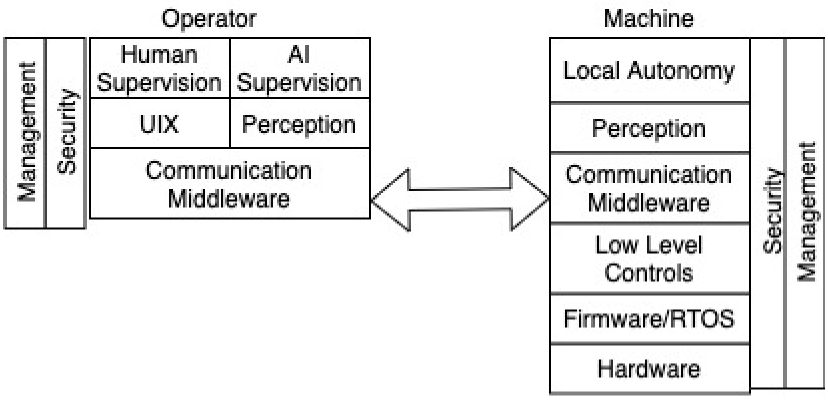


Figure 3: Software architect for the AI driven, supervisory tele-robotics

The tele-robotics stack will need to be a distributed architecture of communicating agents.

The machine-side stack will involve the hardware layer, with a firmware or RTOS, with low level control firmware. A distributed communication middleware will allow all agents to communicate with each other via messages or services. Local perception and autonomous decision making and planning will complete the machine stack. Security and management layers will be additional critical components.

The operator side stack will consist of a User Interface layer which will present information from the machines to the humans in an intuitive way and also accept commands from the operator to relay back to the machine. Augmentation of the human decision making will be done via an independent perception and AI based supervisory layer, which will further make predictions or extract insights and present to the human decision maker.

21.5. Human Robot Interaction

Consumer electronics have made tremendous advancement in terms of interactive devices in recent years. Now we can have an eye gaze tracker, gyroscope and haptic vibrator all inside a single smartphone. The automotive industry is gradually catching up and already commercialized gesture, speech and primitive eye gaze controlled interfaces inside the cockpit. However, human robot interaction still uses joystick based controllers or an application rendered on a touchscreen display for controlling any robotic agent starting from a single robotic arm to drones. This proposal will investigate multiple modalities like speech, gesture, eye gaze and traditional joystick controller for representative tasks involving robotic systems. The project will select a set of representative tasks like drone or robotic arm control and enumerate and compare all possible combinations of modalities with respect to throughput and error. Main objectives will be

1. Investigating different input and output interactive technologies for human robot interaction

2. Developing speech, gesture, eye gaze control based robotic agent providing visual, haptic and auditory output
3. Developing cooperative robotics for people with different range of abilities
4. Enhancing efficiency of operators of robots and semi-autonomous vehicles

21.5.1. Drone Tracking using Eye Gaze

The system will use ocular parameters like saccadic gaze movements and eye gaze fixations to fly an interceptor drone and track another airborne target. The proposed system will enable anyone even without flying experience to efficiently operate UAVs and concentrate on mission control tasks instead of operating the UAV itself.

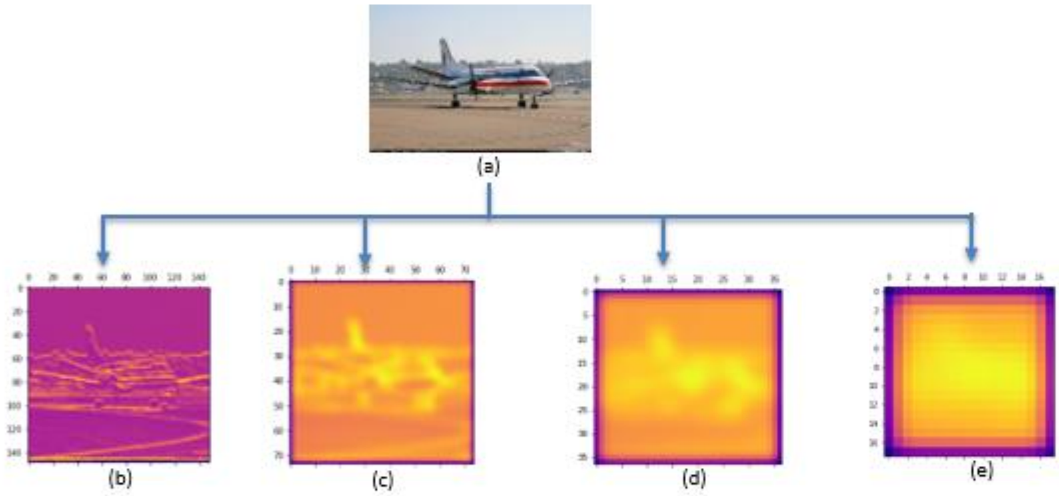
Eye gaze tracking is traditionally used for analysing visual perception but using it as a direct controller of user interface is a new concept and mainly explored for people with different range of abilities. The project aims to abstract raw flying commands from users and will automatically convert users' visual search pattern to flying commands while the drone itself will be intelligent enough to take alternative decisions in face of an obstacle to continue with mission control tasks. Generally, visual search behaviour is considered personalized and specific to the visual search task in hand. However, we mined patterns in visual search behaviour and proposed a visual perception model that can predict visual scan path and search time accurately even for people with a few types of visual impairment. Our target prediction and gaze control interface was tested inside a car plying through a road and in a military aviation environment with operators undertaking realistic flying and mission control tasks in variable G (-1G to +6G) load factors. It may be noted that control input to the drone should not be directly fed from the eye gaze tracker as all saccadic movements may not contribute to visual search and speed of saccadic movement (between 250 and 350 ms) is too fast for the drone to respond. Our proposed solution will leverage basic visual psychology and predictive nature of eye gaze movement and will efficiently convert them to flying instructions after appropriate filtering. We already patented an eye gaze controlled interactive HUD (Appn No. 201941009219 and 201641037828) and are working with the Aeronautical Development Agency to develop eye gaze controlled HMDS for military aviation.

21.5.2. Immersive visualization of Visual and Lidar Perception of Autonomous Vehicle

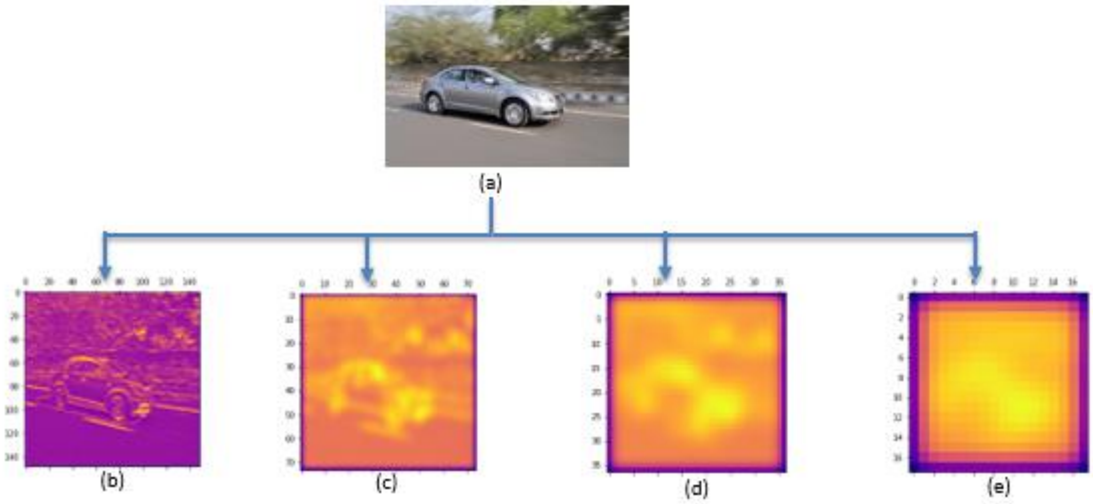
Research problem: Optimizing visualization of Lidar and visual perception of an autonomous vehicle to help in explaining and developing sensor fusion algorithms

Brief Description: This project will use immersive visualization techniques to explain data processing through cameras, Lidar sensors and ultrasound sensor of an autonomous vehicle. The project will create point cloud and mesh from Lidar sensor and augment that with results from CNNs processing visual imagery. The system will simulate the internal processing of different layers of convolution of a standard CNN and help to explain how visual data is used in conjunction with Lidar and ultrasound data for decision making in an automated system. A user can immerse in a 3D road environment with overlaid Lidar and visual data and explore different sensor fusion algorithms. The team already developed preliminary point cloud and mesh visualization for Lidar data and a digital VR twin of a lab with real time sensor data.

As a case study, we trained the VGG16 model (pre-trained on ImageNet) on road object dataset downloaded from kaggle. We have used four classes of objects, i.e. car, motorbike, bi-cycle, and airplane. We trained the model for 50 epochs, with each image resized to a shape of (299, 299, 3), which is required by the pre-trained VGG16 model. To understand how CNN models can classify the input image, we need to understand how our model sees the input image by looking at the output of its intermediate layers. By doing so, we can learn more about the working of these layers. For instance, following are the outputs of some of the intermediate convolution and their corresponding activation layers of the trained VGG16 model, when provided with test images from a test set. We visualized activations in convolutional layer, convolutional layer, convolutional layer, and n convolutional layer as shown in Figure 1. It may be noted that initial convolution layers act as a collection of various edge detectors. At that stage, the activations retain almost all the information present in the initial picture. As we go deeper, the activations become increasingly abstract and less visually interpretable. They began to encode higher-level concepts such as “wings of airplane” and “skeleton of car” and so on.



(a) Input test image; (b) 28th channel of the activation of the 4th layer ; (c) 28th channel of the activation of the 9th layer; (d) 28th channel of the activation of the 13th layer; (e) 510th channel of the activation of the 17th layer



(a) Input test image; (b) 28th channel of the activation of the 4th layer; (c) 28th channel of the activation of the 9th layer; (d) 28th channel of the activation of the 13th layer; (e) 510th channel of the activation of the 17th layer

Figure 1. Visualization of Intermediate Layers of CNN

Deliverable: A 3D virtual walkthrough representative Indian road with overlaid visualization of visual and Lidar data

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21.6. Key technology components and innovation questions

The following table articulates all the components and the various considerations in designing these.

Table 1: Key technology components and innovation directions.

Sub-System	**Aspects**	**Characteristics**	**Technology components**	**Innovation Questions**
Machine	Mobility	Max, Average Speed; Braking; Acceleration; Turning; Reversing;Spinning;	● Energy efficient mobility, ● Autonomous mobility ● Localisation, Mapping & planning ● Exception handling	● Operation in GPS/communication denied environments. ● Low cost techniques for simultaneous localization and mapping. ● Verifiable/guaranteed mobility solution ● Seamless integration of autonomous and supervisory control ● Fusion of sensory information from diverse sources ● Robust operation in variable environmental conditions
	Actuators	Forklift; Gripper; Sprayer; Arm; Movable platform;	● Energy efficient and stable actuations ● Position/Force/ Torque/Impedance control ● PID control	● Novel actuators which are energy efficient, low cost and reliable ● Novel motors

Sensors	Environment Sensing, Proprioception, Location Sensing	● Integration of Haptics, force and position sensors ● Integration of ultrasound, radar, lidars, cameras & microphones ● Integration of FBG sensors	● Texture and touch sensor ● Sensor fusion ● Real-time compression of video ● Real-time compression of lidar data ● Robust estimation from sensed data ● Algorithms for low snr regimes (night/poor weather conditions) ● Fusion of data from sensors in infrastructure and other machines
Wireless Communication	One or more communication options: Sub-GHz, Wifi, Long-range Wifi, 3G, 4G, 5G	● QOS enabled communication stack ● Seamless handover across WiFi access points ● MIMO support ● Low latency communications ● Wifi6, ● CV2X ● 4G and 5G	● Optimal scheduler ● low latency hand-offs ● Reliable and secure CV2X communication in highly dynamic and mobile environments
Electronics	Electronic/S-W interface for all sensor and actuators. Redundancy architecture	● Low power, robust and reliable interface to all sensors/actuators. ● Industry standards	● Low power and low cost and EMI robust interfaces ● Configurable actuator drives ● Power harvesting, Charging and energy recovery ● Embedded sensors ● Robust analog front ends.

Safety, reliability and robustness	Safety guarantees for mobility (geofencing), movement of other parts (force/torque control limits), speed limits, safe behaviour under loss of communication or other failures	● H/w and S/w redundancy	● Provable safety and reliability ● Formal verification ● Co-simulation (of machine-network) frameworks
Compute	Microcontroller running a RTOS to a low end compute with linux to a GPU accelerated linux card	● Microcontroller, CPU and GPU compute framework	● Seamless framework to manage on-machine, edge and cloud compute. Handle hand-overs with minimal disruption
Controls	Hierarchical or shared control - with local control for low level or fully automatable tasks, higher level control to set targets and supervisory control to achieve goals and tasks	● Hierarchical control stack ● Shared control architecture for tasks of multiple granularity ● Integrate traditional with ML based control techniques	● Data driven/learning control for complex actions ● Stability and robustness guarantees in hybrid control.
Security, Identity and Management	CPS security, identity for authentication, logs and management for all hardware and software components	● TPM, Certificates, PUFs and secure communication protocols. ● H/W and Software management stacks	● CPS Security algorithms. ● Data provenance and quality
S/w Stack	Platform Architecture, SLAM, SemiAutonomy, FullAutonomy, Sensor Analytics and Fusion, Planning and reasoning, Redundancy Architecture, Multi-agent support	● RTOS ● Firmware for low level control ● Robust, real time communication middleware ● Local perception and autonomy ● Redundancy for fail-over	● Redundancy and fail-safe algorithms ● Real-time communication middleware and its characterisation,

	Wireless Front end	One or more communication options: Sub-GHz, Wifi, Long-range Wifi, 3G, 4G, 5G	● Integration of commercially available frontends	
	Bandwidth	Uplink Bandwidth; Downlink Bandwidth	● Bandwidth management	● Optimize sensor data processing algorithms for latency/bandwidth tradeoff
	Latency	Round Trip Time	● Continuous measurement of latency.	● Optimizing schedulers and communication parameters to maintain latency bound
	QoS	QOS levels	● QOS negotiation and management with communication network	
Communication Network	Handover	Handover latency	● Low latency handover of communication channels across different access points	
	Redundancy	Multiple links/failover	● Multiple network connections and fail-over protocol	
	Localization Assist	Location accuracy.	● Use RSSI or cell-tower based localization assist	● Algorithms to augment other localization schemes with RSSI
	Packet Loss Rate	Late arriving packet + Lost Packets.	● Monitor and manage stale packets	● Control algorithms to deal with delayed/stale command packets
Infrastructure Assists	Locating Beacons	GPS, UWB, RSSI, Lidar, Ultrasound, Radar	● RTK GPS, UWB installation, drivers and software stack integrated with	● Evaluation of different localization technologies. New innovative,

			system management stack.	low cost, robust technologies
	Sensors	Vision, Lidar, Ultrasound, Radar	● Lidar and radar installation and software stack to feed information to operator and machines	● High speed radar, lidar and video data processing and fusion. ● Binaural audio processing ● AI/ML driven extraction of significant and complex features and events.
	Edge Compute	Edge Processing Capability	● Edge compute to handle processing of lidar, radar and camera data.	● Edge -cloud compute framework, with provision for mobility
Operator System	Haptics; Display; Microphone, VR; AR; Smartphone	Force feedback, Scene rendering from perspective, immersive rendering in VR/AR, Fusing and interpreting multiple sensing streams, processing and relaying sensor data for easy decision making	● Information rendering on displays (including head mounted) ● VR system ● AR system. ● Exoskeleton system ● Fusion/selection of information from multiple machines. ● Authentication and security enabled	● Optimal fusing and rendering of information from diverse sensors, e.g., fusion of lidar and RGB to render 3D views.; ● Low latency fusion. ● Fusion of information from multiple machines. ● Real time object tracking and depth perception in AR media using low cost computing platform. ● Prediction-based rendering to compensate for latencies. ● Addressing accommodation-vergence problem for AR media ● Optimizing resolution and latency in VR media using low

				cost computing platform ● Optimum placement of haptic feedback system with respect to user like at palm, elbow, leg and so on ● Optimum amplitude and resolution of haptic feedback for users in different context of use ● Modifying Head Related Transfer Function (HRTF) for 3D audio ● Finding cost effective solution to deliver haptic and 3D audio feedback for large number of users
	Smartphone; Joystick; Vision Processing; Pilot/Driver Jig;Headset; Gloves; Exoskeleton Speech;	Ease of use and learnability, degrees of freedom that are controllable, impact on human's well being (nausea etc), compute requirements, error rates, speed and latency	● Low latency communication of commands; ● Support command of multiple machines; ● Authentication and security enabled	● Speech and NLP based mapping of intent to actions. ● Gesture based command support. ● Multi-lingual support. ● Easy adaptation to new users. ● Coordinated command/super vision of multiple machines. ● Decision support by incorporating additional information from other sources (like infrastructure sensors etc). ● Evaluation of optimal User Interfaces which maximize

				productivity while minimizing cost. ● Mixed reality rendering on (headset) displays by fusing multiple sensors such as lidar and RGB.
	Calibration/adaptation to user/machine	Calibration methodology, complexity, frequency, degree of adaptability	● Self/auto calibration of operator interface to machine environment	
	Modality Selection	Selecting input and output modalities of operation for different applications	Selecting among input modalities like hand and finger movement, speech, eye gaze and output modality like AR/VR system, haptic and spatial audio output	Integration of multiple modalities to generate realistic immersive experience Multimodal Fusion and Fission algorithms
	Visual Rendering Media Development	Developing and Configuring AR/VR/MR media platform	Operators console development Showing real time visual feedback to operator	● Real time object tracking and depth perception in AR media using low cost computing platform ● Optimizing resolution and latency in VR media using low cost computing platform ● Integrating prediction algorithms described in user model section with AR/VR interaction ● Rendering eye

				gaze controlled interactive objects in AR/VR applications
	Non Visual Rendering Media Development	Developing audio, haptic, olfactory and gustatory feedback systems	Operators can touch and feel remote object	● Optimum placement of haptic feedback system with respect to user like at palm, elbow, leg and so on ● Optimum amplitude and resolution of haptic feedback for users ● Developing Head Related Transfer Function (HRTF) of able bodied users for users ● Finding cost effective solution to deliver haptic and 3D audio feedback for large number of users

21.7. State of the Art

21.7.1. Multimodal Cobot

Use of non-traditional modalities for Human-Robot Interaction (HRI) is not a new concept although using it for people with severe disabilities remains challenging. Bannat [2009] and colleagues used direct voice input, eye gaze and soft buttons for controlling a robot in an assembly process. Alsharif [2016] and colleagues configured eye gaze movement, eye blinks and winks to the 7 degrees of freedom of a robotic arm and evaluated performance of the system with 10 participants including one person with motor impairment for a block rearrangement task. Stiefelhagen [2007] and colleagues investigated direct voice input, pointing gestures and head orientations and reported results on accuracy of each individual modality. Palinko [2016] and colleagues compared eye and head gaze based HRI for a tower building task and reported significant reduction in task completion time and increase in subjective preference for eye gaze tracking system compared to head tracking system. Nvidia and ITU Copenhagen [2014] published articles on gaze controlled drones achieving primitive movements by following the eye gaze of an operator although the system is not yet aimed for people with different range of abilities. Bremner [2016] and colleagues investigated the effect of personality cues of a robotic tele-avatar like gesture, speech and appearance on its perception by the operator. They also reported that the perception and individual behavior of operators is subjective and vary for individuals and concluded that any human robotic system should be designed considering the user background, perception and behavior. Similar findings were reported by Leite and colleagues [2012] who evaluated the empathic behavior of an autonomous social robot and reported that empathy facilitates the interaction and affects positively the perception of the robot. Kohlbecher [2012] aimed to model human gaze behavior and head movement and used it for a robotic head interacting with the environment based on input from a user and reported improvement in human performance in terms of velocity and acceleration. Kim [2001] developed a real time eye tracking system and proposed its use in eye gaze controlled HRI for people with different ranges of abilities. The eye gaze was captured as an image by CCD cameras and processed further for head movement compensation. The setup gave accurate results within a range of 2m. However, they reported evaluation of the system for just one user with two use cases. Zaira [2014] investigated controlling robot prostheses with eye gaze control and evaluated the system with 9 able-bodied participants. Zhang [2019] used eye tracking enabled HMD to operate a remotely located robot and so far reported user studies with able–bodied participants. Chen [2014] used Electrooculography to detect eye gaze movements and used it to control robotic movement in 8-directions. The system is tested with five able-bodied participants. Fujii [2013] used Hidden Markov Models (HMMs) for gaze gesture recognition that can enable a surgeon to control a 6 DoF camera through real time gaze gestures in 2D whilst simultaneously enabling both hands to focus on the operation. Lin [2012] used eye tracking goggles to move a wheelchair while Kuno [2003] used face direction for the same. Dziemian [2016] explored eye gaze controlled interface and a screen mounted low cost eye tracker to move a prosthetic arm but did not use video see through display and evaluated the system with only one able-bodied user. The Camera mouse system used to track nostrils for head tracking instead of eye gaze tracking and Betke [2002] reported "There has been some success in tracking the eye, but not to the extent of determining gaze direction".

Use of intelligent robotics is not just limited to support people with different range of abilities but also undergone many design iterations to assist humans in workplace, factories and industries [Graser 2013, Peshkin 2001]. Such robots which physically interact with humans in a co-working place sharing payload with humans are called COBOTs (COllaborative roBOTs). Based on their level of interaction, COBOTs can be classified into three categories as Co-existence – minimum interaction with no workspace sharing. Cooperation – workspace is shared with no simultaneous intervention and Collaboration- shared workspace where robot and human work simultaneously [SICK Sensor Intelligence, 2019]. Applications of Cobots include complementing the skill of a human labor in manufacturing and molding by using an intuitive and adaptive graphical user interface (GUI) [Koch 2017]. Cobots are also helping surgeons perform high precision surgery by optimum sensor fusion and virtual reality simulations for best surgery results [Bonneau 2004]. Robots are assumed to play the roles of supervisor, operator, mechanic, peer and bystander in the era to ever-growing technological advancements [Dautenhahn, 2005]. Search and rescue robots which can be remotely operated where humans and robots can work as peers. Robots can also work in proximity to humans as in Assistive Robotics where robots can be used as a tool or can act as a mentor aiding the blind, therapy to the elderly and social interaction support to autistic children [Leite et al, 2012]. CoBots have also found use in homes and robot maids, vacuum cleaner and even robot construction [Goodrich 2008].

With the expansion of robotics application fields, robots always face unpredictable manipulation tasks in hazardous and unstructured environments. Teleoperation approaches show great potential in assisting the operator to perform and accomplish complex and uncertain tasks. Naijun Liu [2019] and colleagues designed a robot teleoperation system based on virtual reality devices. The teleoperation system mainly includes virtual reality devices, cameras, and a robot arm. With a headset mounted on the head, the operator can see the robot working scenario in real time, and assist the robot to accomplish complicated manipulation tasks. Experiments show that the designed system can efficiently perform complicated manipulation tasks with high accuracy and stability.

The man-machine interfaces are achieved by mechanical equipment such as mouses, joysticks and so on. But the physical abilities of the human are required for these controllers, which is not applicable to the disabilities. Thus, to satisfy the needs of the physically challenged, the brain computer interface is developed for the robot control systems. Yuxia Yuan [2018] and his colleagues propose a brain-teleoperation control strategy that combines the deep learning technique (DLT) to realize the control and navigation of a mobile robot in unknown environments. The support vector machine algorithm is utilized to recognize the human EEG signals in the brain-computer interface system. In this way the intentions of humans can be distinguished and control commands are generated for mobile robots. The DLT is used to recognize the type of environmental obstacles and environmental features.Three volunteer subjects are invited to test the entire system, and all operators can successfully complete experiments of manipulating the robot in corridor environments. The application of human-computer interface could potentially lead to robotic devices and other sophisticated neural control bionic prosthetics for the disabled people.

Keeping humans "in the loop" appears to be indispensable as they are best able to monitor autonomous agricultural machines in the field. N.Murakami [2008] and his colleagues developed the teleoperation system for agricultural vehicles. The system was developed to satisfy the needs of various farm operations and teleoperation in unknown agricultural fields. The vehicle can travel autonomously by using an RTK-GPS and a fiber-optic gyroscope during supervisory control, and the operator interface also provides a field navigator based on Google Map technology. The results of field tests using direct control showed that it is difficult for the operator to control the movement of the vehicle along the target lines.

22. Appendix F: Microbots

22.1. Executive Summary

Develop technology solutions addressing the core problems of modern micro-robotics, especially those related to their deployment in biomedical applications. The specific challenges to be dealt are related to (i) powering and imaging remotely manoeuvred micro/nanobots deep inside an animal, (ii) on-board electronic and MEMs devices for both in vivo and ex vivo sensing and signal processing, and (iii) controlled assembly and analysis of living cells combining microfluidic and MEMs technology platforms.

22.2. Context and Goals

The ability to manipulate both living and non-living systems at micron and sub-micron length scales can revolutionize technologies of the future, especially in the areas of healthcare and diagnostics. A group of faculty members at IISc have formed a core group on robotics leading this effort, where the whole team comprises of participants from multiple departments at IISc, as well as representatives from medical community outside IISc. The main efforts of this group during the tenure of the proposed project will be directed along the following lines:

We will develop a microrobotic platform for controlled capture, assembly and analysis of living cells by combining mechanical, optical and microfluidic technologies. We will explore robotic geometries with multiple spatial degrees of freedom and harness their interactions and nonlinearities for enhanced sensing and on-board signal processing capabilities. These initial efforts will be focussed toward ex vivo applications.

We will develop micro/nanobots that will eventually lead toward biomedical technologies of the future, leading toward controlled manipulation of a swarm of robots deep inside a living animal. We will develop crucial components of this futuristic technology: powering microbots using bodily fluids (e.g. glucose), rendering them bio-degradable while integrating sensing capabilities using on-board electronics, and demonstrate their controlled manoeuvrability deep inside an animal using image-guided navigation.

22.3. Proposed Activities

A brief description of the proposed activities is given below:

Capturing and analysing single cells or a small cluster of cells will augment future surgical procedures. Initially the focus will be to design and develop the microfluidic chip which will enable ex-vivo capture of such cells and cell clusters. In the next step, it would be beneficial to perform sub-cellular sampling without disrupting the whole tissue, through localised cell poration. Incorporating force feedback and high-resolution confocal imaging with microfluidic devices, localised poration will be demonstrated. Once capturing has been optimised, we will integrate various sensing technologies with the microfluidic devices.

An exciting possibility in tissue engineering is in situ assembly of cells and tissue fragments injected into the body using microrobots. An example of this is injecting retinal cells cultured on microrobots into the eye, assembling them into shape, and placing the assembled retinal tissue in the right place. This is likely to simplify the surgical procedure. Towards this, we want to demonstrate polymer microrobots navigated in a fibrous environment, being attached to one another to form a shape, and then detached at the end. Externally applied magnetics actuation will be used by embedding magnetic nanoparticles inside the polymer microrobots.

Feature reduction for real time unsupervised deep learning is a challenge that has not been met so far. We propose to build a human cochlea inspired hardware-based real time high-resolution Fourier transform for deep learning applications. We will initially start out by designing and fabricating a chip with MEMS/NEMS based analog Fourier Transform to demonstrate feasibility of this notion of analog

Fourier Transform. Next, we will develop an interface for a neural network to accept feature reduced inputs from a single sensor at first followed by multiple sensors.

MEMS microrobots have traditionally possessed a limited number of degrees of freedom. Further, independent actuation of the joints in a MEMS robot has been a challenge. Here we would investigate the development of a MEMS microrobot which possesses multiple ball-and-socket joints, each of which can be photothermally unlocked individually and actuated magnetically. In addition to design and fabrication, we would also investigate measurement of joint angles and their subsequent control. Finally, applications of such MEMS robots in cell and tissue manipulation would be explored.

Nanoelectromechanical Systems are essentially nanoscale robots that can be used to sensing as well as actuation. This ability to manipulate motion and sensing at these extreme dimensions make these systems extremely valuable for microrobotics. We propose to develop sensors based on these tiny vibrating structures which would utilize nonlinear interaction between them to improve the sensitivity.

For image guided navigation of the magnetic nanobots, we will first optimize the functionalization protocols of the PET labels on the nanobots and incorporate appropriate contrast agents with the magnetic layer of the nanobot structure. Once optimized, we will demonstrate their imaging in phantoms and then deep animal tissues. Finally, we will demonstrate image guided navigation of the magnetic nanobots inside a living animal.

Self-powered motion is a crucial factor for deploying far and wide-reaching applications of autonomous micro or nano-robots. As healthcare is one of the major application domains being considered for microrobots, we want to develop a micro-scale fuel cell technology which can generate power from the oxidation of glucose which is abundantly available in the human body. In particular, we will develop an enzyme-free solid-state micro-fuel cell (10 – 100) microns square with power densities in the range of 1-5 microWatt/cm^2.

The proposal also investigates novel therapeutic technologies based on ingestible microelectronic systems; which can be used as in vivo biodegradable sensors as a part of our “fantastic voyage” program. A unique feature of this development is the fact that all components comprising the electronics are harmless to a human child and can be digested by the body. Shaped as a pill, the device when swallowed senses clinically important parameters and radios the information to the outside world.

22.4. Prior Work

A major component of the research program developed by Ambarish Ghosh comprises of helically shaped nanorobots that can driven in fluidic and gel-like media using small magnetic fields. These robots can be rendered multifunctional (optical, chemical perturbations, mechanical measurements) [1] and can be maneuvered in complex heterogenous environments, including intracellular spaces [2] with high spatial resolution. Group led by Akshay Naik is interested in physics and application of nanoelectromechanical systems. In particular, the group is interested in nonlinear interactions [3,4] between different devices and its manipulation to improve their performance. G R Jayanth’s group has been interested in precision [5-8] motion measurement and control, for applications in imaging and manipulation of micro- and nano-scale objects. His group has developed multi-degree of freedom probes for atomic force microscopy and has demonstrated their use in 3D nanometrology. Sanjiv Sambandan’s group is interested in semiconductor devices and integrated circuits with a special focus on integrated circuits fabricated on flexible and wearable substrates and investigate self-healing [9, 10] phenomena. The key component in realizing an analog Fourier transform is a MEMS based resonator. The research program developed by Saurabh Chandorkar deals with building and understanding various performance features [11,12] of MEMS based resonators such as energy loss mechanisms, non-linear behaviour and phase noise. His lab also works on wafer scale packaging of MEMS devices. This research requires expertise in mechanical design, analog circuits and measurement techniques as well as extensive knowledge of microfabrication technology. G. K. Ananthasuresh's group has been working on SU-8 polymer microrobots and using them for cell-culture applications. In particular, a cell-stretcher mechanism has been designed, microfabricated [13], and tested with cells cultured on it. It is demonstrated that forces applied by the cells on the substrate can be measured in real time. The cell-stretcher mechanism is integrated into the scaffold on which cells are cultured. Furthermore, the group has expertise on designing the stiffness of the scaffolds as desired. Since the scaffolds, made of SU-8 polymer, can be embedded with magnetic nanoparticles, they can be actuated to provide dynamic microenvironment for the cells. Additionally, the group has worked on modeling magnetic actuation and attach-detach microrobots [14] using externally applied magnetic fields. Recent research projects in Manoj Varma lab has dealt with individual and collective motion of bacteria at the microscale [15, 16]. Based on these studies, a broad program has emerged in his lab which seeks to leverage the knowledge obtained from the study of biological systems into synthetic mirorobots based on conventional microfabrication techniques. Manipulating cells and cell clusters in microfluidic platforms has been studied by the Microfluidic Devices group led by Prosenjit Sen. Technologies developed in the lab enables 3D manipulation of cells using different actuation [17] mechanisms. Controlled manipulation of cells and cell clusters have been used to perform multi-modal analysis, capturing their electrical [18], mechanical and bio-chemical properties.

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22.5. Research Objectives

One of the holy grails of modern robotics is to be able to drive therapeutic nanovehicles to diseased sites inside living beings. Among various approaches, the strategy opted by the IISc micro/nanorobotics group working on magnetically driven helical nanobots is particularly attractive due to its non-invasive powering mechanism. Although there have been prior reports of manoeuvring these system of nanobots under in vivo conditions, including peritoneal cavity and vitreious humor of the eye, all of these prior demonstrations were limited by depth of imaging inside the scattering environment of biological tissues, and therefore not applicable to organs deep inside the body. We propose to overcome this challenge by integrating a dual imaging modality (PET/MRI) with the nanobots and then demonstrate live image guided navigation of the nanobots deep inside an animal. We believe this will be an important step toward realizing the ambitious dream of “fantastic voyagers” carrying out theragnostic tasks in biomedicine of the future.

Power generation at the micro-scale is still an open problem. Several solutions such as the use of muscle cells, shape-memory alloys etc have been explored. A scalable, easy-to-integrate solution is still lacking. We believe that a CMOS compatible solid-state enzyme-free option will provide a solution to micro-scale power generation which will be easy to integrate to future micro-robots, or implanted micro-sensor systems.

Even though a wide variety of microfluidic tools have been developed for analysing biological samples (including cells, cell clusters, etc.), the analysis still remains a post-facto activity. It is envisioned that the future of micro-robotic surgery will be enabled by both tethered and untethered microfludic devices which can perform in-vivo localised analysis of biological samples. The main challenges of such a microfluidic based platform remains in, precise flow and force control through real time feedback from high-resolution imaging. Development of this platform will significantly enhance current surgical tools and techniques.

One of the major challenges in computing is the creation of machines that can learn unsupervised in real time with energy efficiency akin to the human brain. In recent years, several advances have been made in development of machine learning algorithms and energy efficient hardware such as neuromorphic circuits which successfully target applications such as speech recognition and computer vision. However, for applications such as unmanned vehicles, strategic military needs and healthcare based on cognitive capability of real time learning and decision making, the fundamental problem that needs to be addressed is feature reduction of large scale data acquired from multitudinous sensors.

Taking inspiration from human cochlea that processes acoustic waves in real time to achieve feature reduction via real time Fourier Transform, we propose to develop MEMS based platform for carrying out ultrafast low power Fourier Transform of output of any arbitrary sensor with an electrical output which can be interfaced with an artificial neural network to achieve real time feature reduction.

The recent years have seen a surge in the development of wearable electronic devices for health care diagnostics. These devices have migrated from the originally intended non-invasive applications (eg. pulse, temperature monitoring) to invasive deep-body implants (eg. smart catheters, electrodes inside the skull for EEG signal pickups, antennas for wireless power transfer to pacemakers etc). We intend to initiate a new thread of research which is the first of its kind in the world. Using the unique developed process of building 3-D structures with a form of sugar, we intend on building electronic devices that can be ingested safely. Thin film circuits are developed on sugar (isomalt) and embedded in cellulose capsules (standard medical grade). This pill is ingestible, and the electronics remains active for a short duration. In this short duration, the electronics senses a clinically important aspect in the alimentary canal and radios this information to the outside. A receiver outside the body collects this information. Materials and volumes are chosen to make the pill harmless. There are many possible circuits depending on the application. (i) For location sensing, an LC oscillator alone suffices. Common RFID frequency bands are 125 kHz, 13.56 MHz, 433 MHz to 900 MHz. For maximum power transfer to/from deep body implants, 900 MHz was shown to work best. As a starting point, we design for the standard 13.56 MHz channel.

While macro-scale industrial robots have revolutionized manufacturing and medicine, a corresponding revolution has not occurred with the use of micro-robots in microfabrication. While one of the reasons for this has to do with the strategy for fabrication at the micrometre scale being different, viz., batch fabrication, there still exist opportunities during micro-assembly where micro-robots can play invaluable roles. However, MEMS robots reported in literature generally possess limited degrees of freedom at their joints and limited range along each axis. Further, unlike macro-scale robots, independent actuation of the joints in MEMS micro-robots has not been realized. In this project we would develop MEMS microrobots whose joints can be photothermally unlocked and magnetically actuated. This feature addresses the two lacunae of MEMS robots and would lead to greater sophistication in their structure and function. We would explore application of such robots in manipulation of cells and tissues.

In situ assembly of cells and tissue fragments in dense fibrous environment is the principal challenge that will be addressed in this segment of the proposed project. The following work-packages are planned:

(i) Designing 2D SU-8 microrobots endowed with snap-fit mechanisms for attaching and detaching; their microfabrication using photolithographic patterning after embedding them with magnetic nanoparticles.
(ii) Design and fabrication of an array of planar electromagnets for localized magnetic actuation concurrently setting up Helmholtz coils for global control.
(iii) Demonstrating navigating, attaching, and detaching microrobots using magnetic actuation first in air and liquid environment and finally in dense fibrous environment.
(iv) Culturing cells on microrobots and testing the feasibility of joining cells with mechanical intervention of actuating and assembling microrobots.
(v) Assembly of cells in fibrous environment using magnetic actuation (the final goal of this segment of the proposed project).

22.6. Technology/Product Development

The research carried out can lead to various technologies and products of commercial relevance, primarily but not limited to the area of healthcare. Examples include:

(i) Multimodal nano-imaging technologies which are of relevance to healthcare, especially cancer.
(ii) Microscale fuel cells for biomedical applications: The proposed research can lead to the availability of a power source in the range of 1 – 1000 microns square range which is of high relevance to future biomedical implantable systems.

(iii) Micro-fluidic surgical devices for sampling and analysis of clusters, cells and subcellular components during various medical procedures.
(iv) MEMS based platform for carrying out ultrafast low power Fourier Transform of output of any arbitrary sensor which can be interfaced with an artificial neural network to achieve real time feature reduction.
(v) NEMS devices that utilize nonlinear effects to improve the sensitivity of the devices.
(vi) Edible pill with micro-electronics to enable sensing of clinically important parameters in the oesophageal tract.
(vii) MEMS microrobots with multiple individually addressable, and magnetically actuated ball-and-socket joints
(viii) SU-8 polymer microrobots that can be navigated, attached to form desired shapes, and detaching on demand.
(ix) Assembling biological cells using microrobots.