ISSN No. 0971–4413

Technology Focus

टैक्नोलॉजी फोकस

A Bimonthly S&T Magazine of DRDO

Vol. 24 No. 6, November-December 2016

Intelligent Mobile Robotics

From the Desk of Guest Editor

Centre for Artificial Intelligence and Robotics (CAIR) is one of the key laboratories of Micro-Electronics Devices & Computational Systems (MED&CoS) cluster. CAIR has excelled in design and development of cutting edge technologies in the domains of Artificial Intelligence, Robotics, Command and Control, Networking, Information and Communication Security leading to development of mission critical products for secure battlefield information systems, communication, and management systems.

This special issue of CAIR focuses on a key vertical at CAIR, 'Intelligent Mobile Robotics', covering CAIR's ability in the multi-disciplinary design and development of mobile robots and the associated intelligent algorithms.

CAIR has worked in several enabling technologies for realisation of intelligent mobile robots. These include design of robotic manipulator arms and mobile robotic platforms, perception technologies using multi-modal sensors and Artificial Intelligence algorithms. Using these technologies CAIR has developed various systems which include manipulator arms for the non-destructive testing of LCA components and steam generator of nuclear power plants, a variety of mobile robotic platforms with different locomotion methodologies and Autonomous Unmanned Ground Vehicle (AUGV).

One of the key technologies for realisation of Intelligent Mobile Robots is the capability of the robot to understand its environment and react in a context sensitive manner. This task requires simultaneous planning, localisation and mapping. As the robot traverses its environment, it builds the map of the environment and localise itself in the map. Further, it plans its next course of action to achieve its mission objectives. CAIR has progressed significantly in creating algorithms for navigation in indoor and outdoor environments.

The future intelligent robotic systems would make use of heterogeneous robots operating in a collaborative manner to achieve the mission goals. CAIR is presently developing Multi Agent Robotics Framework (MARF) through a multilayered architecture for enabling collaboration amongst a team of robots. The heterogeneous composition and collaboration capability can effectively contribute to a myriad of military applications, such as surveillance, exploration and mapping, search, and rescue, etc.

Recently, CAIR has started work on development of dependable intelligent mobile robots. Well-designed robotic systems will become self reliant, adaptable and fault tolerant, thereby increasing the ease and guarantees with which complex tasks can be handled autonomously.

Technology Focus is a medium through which we get an opportunity to create awareness about the technologies developed/being developed by DRDO. This issue gives an overview of some of the indigenously developed mobile robots and relevant intelligence algorithms.

Sanjay Burman
Distinguished Scientist and Director, CAIR

Intelligent Mobile Robotics

Robotics for defence has constantly progressed through indigenous synergies in diverse multi-disciplinary technologies. Extrinsically, it has been driven by the current military scenario which demands unmanned systems with the ability to operate in an autonomous or semi-autonomous mode, under varied environmental conditions and terrain. Intelligence and mobility are critical enablers for unmanned systems targeted for military operations. Terrain structures vary throughout the Indian landscape. Mountainous, desert, rural, urban, outdoor and indoor, each present a unique locomotion challenge to a robotic platform. Extensive research in locomotion technologies has been underway to cater to specific needs of these terrain types.

Robots navigating on their own and performing even the most basic tasks require a multitude of algorithms running continuously and concurrently to make decisions towards achieving the end goal. These algorithms together constitute the intelligence exhibited by a robotic platform. These technologies have been evolving through advances in Artificial Intelligence (AI).

Enabling Technologies

Realisation of an intelligent mobile robot requires the development of the physical body capable of locomotion and manipulation, incorporation of various sensing capabilities and implementation of intelligent algorithms. While sensory payloads enable a robotic platform to understand its environment, intelligence algorithms enable the robot to plan and act in the given environment consistent with its physical capabilities to achieve the mission objective in a rational manner.

Robot Locomotion and Manipulation

Various types of terrains encountered in an application scenario require the robot to negotiate a path through them. While wheeled platforms are suitable for urban flat terrains, tracked, legged, or hybrid mechanisms are required for more complex terrains.

Locomotion is an important technology which impacts the design of a robotic platform and ensures the stability of the robot structure while moving through the terrain. Robots might, on occasion, be required to interact with their environment. For example, in IED handling applications, the robot might be required to pick up an IED detected by the perception system. This would require the robot to be equipped with a manipulator arm that would be controlled in conjunction with the perception system to handle the IED.

The technology of manipulator arms, including the kinematics and dynamics (forward and inverse), simultaneous multi-axes control and trajectory planning and execution, is thus an important enabling technology for intelligent robotic systems.

CAIR has developed mobile robots with various locomotion techniques and robot manipulators for various applications. Some of the experimental mobile robots have been fabricated using the rapid prototyping facility, RUPAK (RUpan PrAtirupan Kendra), established at CAIR. This facility has 3D printers capable of fabricating parts in plastic, rubber and metal. The various robots developed are:

Wheeled Robot with Passive Suspension

The robot uses six actuated wheels for locomotion. It has bogies on the sides and a four-bar fork in the front to enable it to adapt to the terrain it is traversing for increasing traction and stability. This design enables it to negotiate rough terrain and move over steps upto 200 mm height.

Wheeled Robot with Passive Suspension

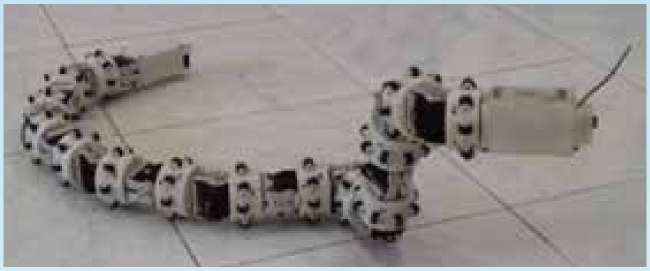
Tracked Miniature Unmanned Ground Vehicle (MINIUGV)

The MINIUGV uses tracked locomotion to negotiate rough terrain and features found in a typical urban terrain including steps and staircases. It is a remotely-controlled man-portable robot which can be used for surveillance and reconnaissance in low intensity conflict operations. It can negotiate stairs with maximum rise of 200 mm and 30 degrees slope, steps with a maximum height of 300 mm and trenches with a maximum width of 500 mm. It weighs 28 Kg and is capable of a maximum speed of 3 Km/h. Its payloads currently include a daylight camera and a wireless link for non-line of site communication of up to 150 meters. It has an endurance of 4 hours on flat terrain and can carry additional payloads up to a maximum 50 kg over flat terrain. The staircase climbing capability along with a live camera feed makes it a perfect choice for counter-insurgency operations.

Miniature Unmanned Ground Vehicle

Snake Robot

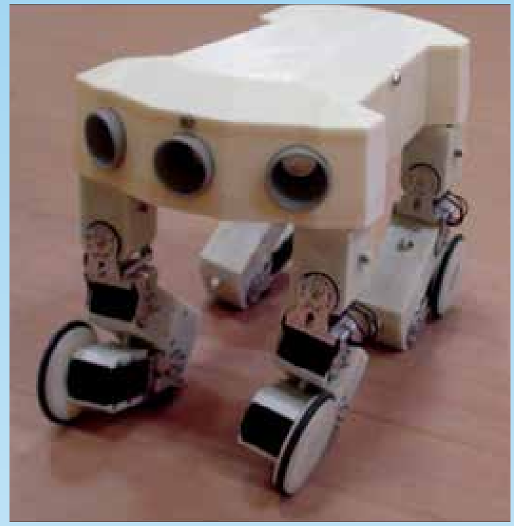
This robot demonstrates concepts of whole body locomotion. The snake robot has 14 active joints. Lateral undulation, side winding, and rolling gaits have been implemented on this robot. A colour camera mounted in the hood of this robot provides video feedback.



Snake Robot

Legged Robots

CAIR has developed six and four legged robots. These robots have three degrees of freedom legs giving them omni-directional motion capability. The robots have been equipped with ultrasonic sensors for obstacle detection and avoidance. The hexapod, six-legged robot, has reptilian leg configuration while the quadruped, four legged robot, has mammalian leg configuration. The quadruped has additionally been provided actuated wheels to enable hybrid locomotion capability. These platforms have given an insight into the implementation of stable gaits for legged locomotion.



Legged Robots: Hexapod and Quadruped

Wall Climbing Robot

The wall climbing robot is a miniature tracked robot capable of climbing vertical walls. It uses an impeller to generate suction to adhere to walls. It has an onboard colour camera for video feedback. The camera is mounted on pan-tilt unit.

Wall Climbing Robot

Robotic Manipulators

Robot arm manipulators have been developed for bespoke applications, including ultrasonic non-destructive testing of LCA components, hot-slug handling and eddy current NDT of heat exchanger tubes in steam generators. Various configurations of robot arms have been developed, keeping in view the specific workspace requirements of each application. These include 5-axes gantry systems, 5-axes articulated-SCARA hybrid configurations and six-axes articulated configurations.

The technologies developed include coordinated multi-axes motion control with trajectory planning and profiling in Cartesian and joint space, link parameter calibration and visual serving of the end-effectors.

Efforts are currently underway to incorporate manipulator arms on intelligent mobile robots and develop advanced algorithms that utilise the additional degrees of freedom and perception inputs provided by the mobile base into the planning and execution of the manipulation task.

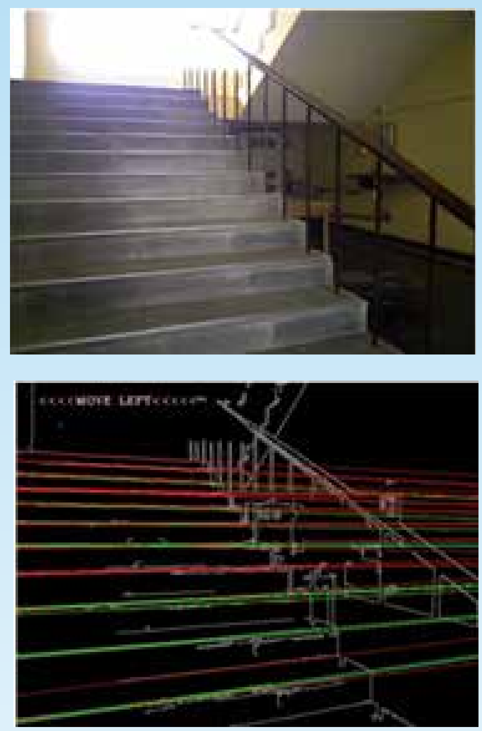
Manipulator for NDT of LCA Components, Hot-slug Handling and Eddy-current Testing of Steam Generator Tubes

Robot Perception

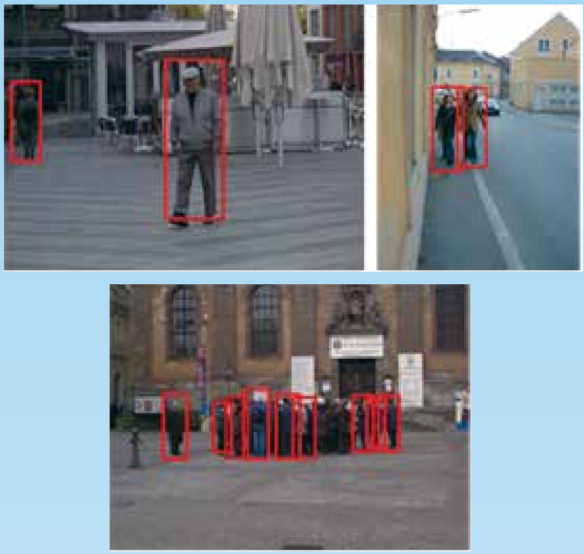
To understand its environment, a robot is required to sense, perceive and plan. For navigation, it must sense the presence of positive (rigid objects) or negative (pits) obstacles. A robot should be able to perceive easily navigable (low cost) areas. For searching and identifying objects, it must perform object detection. Such technologies require sensors which capture data that can be processed to understand and interact with the environment. The most common sensors used onboard intelligent robots are LiDAR, camera, ultrasonic range sensors, RGBD sensor, odometers, GPS, IR, and IMU. Some special applications demand specific sensors such as Nuclear, Biological or Chemical (NBC), explosive detection, etc.

The use of perception algorithms evolve and adapt as per the needs of the robot and its targeted applications. CAIR has an advanced effort in the perception technology. Camera images have been used to align a tracked robot to staircases before it embarks. Camera-based tracking feature in combination with human detection enables human following capability. For navigation, it must sense the presence of obstacles, clear areas, mark various regions such as road, footpath, traffic sign, etc.

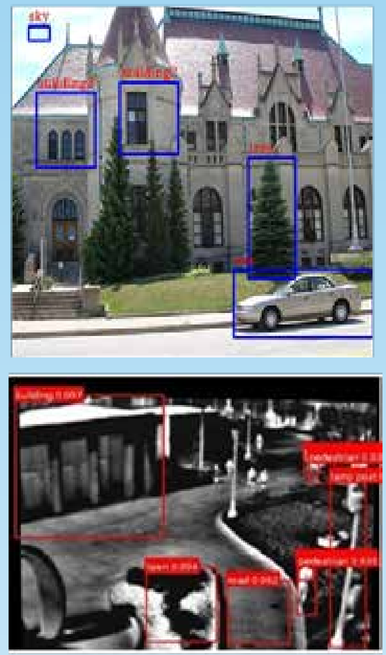
This capability requires the object detection algorithms. Wheeled outdoor robots use camera images to segment traversable roads. The road segmentation plays a critical role in identifying traversable and non-traversable road. Advance computer vision processing techniques have been augmented with machine learning approaches, such as deep learning, to increase the precision and accuracy of perception algorithms.



Staircase Alignment Detection

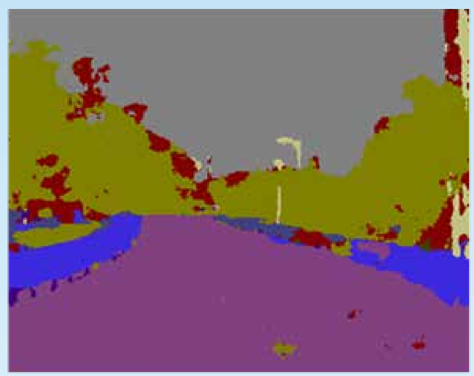


Human Detection in Optical Images (Red rectangle marks the detection of the algorithm)



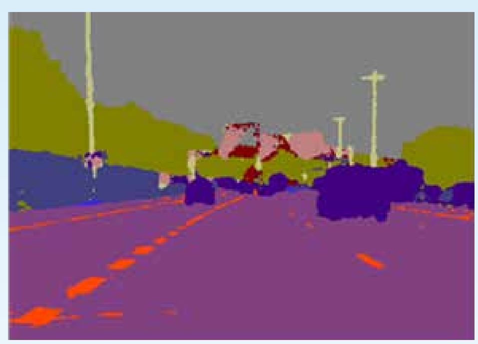
Object Detection in an Optical and in an IR image

(a)



(b)

(c)

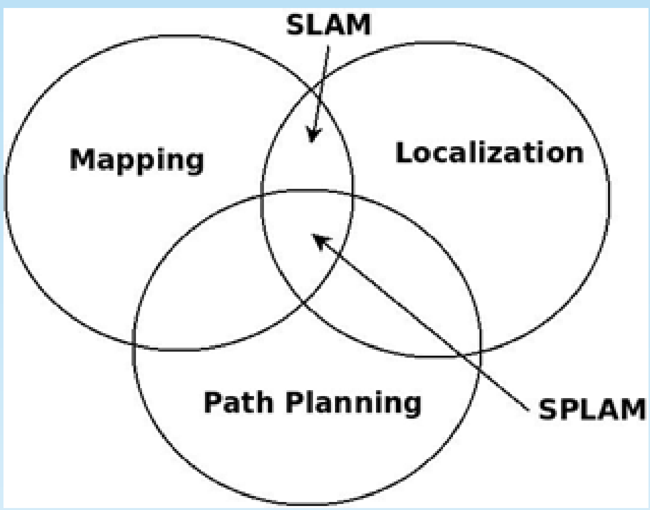


(d)

Road Segmentation in an Optical Image. (a) and (c) are input Images; (b) and (d) are the Corresponding Segmentation Results

Artificial Intelligence Algorithms for Autonomous Navigation

Autonomous navigation is the critical requirement for intelligent mobile robots. To autonomously navigate in an environment, a robot must perform Simultaneous Planning, Localisation and Mapping (SPLAM). A robot must execute localisation, mapping and planning concurrently to successfully handle the dynamic entities in the operational environment. In absence of any of these activities, a robot will not be able to move autonomously in real life deployment scenarios. These activities are as follows:



Interaction of Localisation, Mapping and Path Planning Activity for Autonomous Navigation

Localisation

Localisation is the process of knowing where a robot is located in the world. It is important for the robot to know where it is to execute its plan. Localisation can be achieved using a GPS sensor as well. A low cost GPS usually has errors in order of meters. Other problems include unavailability of signals in indoor or in heavy foliage environment, multi-path errors to list a few. Localisation algorithms have been established using proprioceptive sensors such as LiDAR (2D & 3D), mono and stereo vision sensors, which provide sufficient accuracy and work in the absence of GPS or any other external localisation system. (Proprioceptive is a term borrowed from psychology and relates to stimuli that are produced and perceived within an organism, especially those connected with the position and movement of the body.) Bayes Filtering algorithms such as Particle Filter, EKF (extended Kalman Filter), UKF (unscented Kalman Filter), etc. are being used to estimate localisation by fusing information available from multiple sources.

Mapping

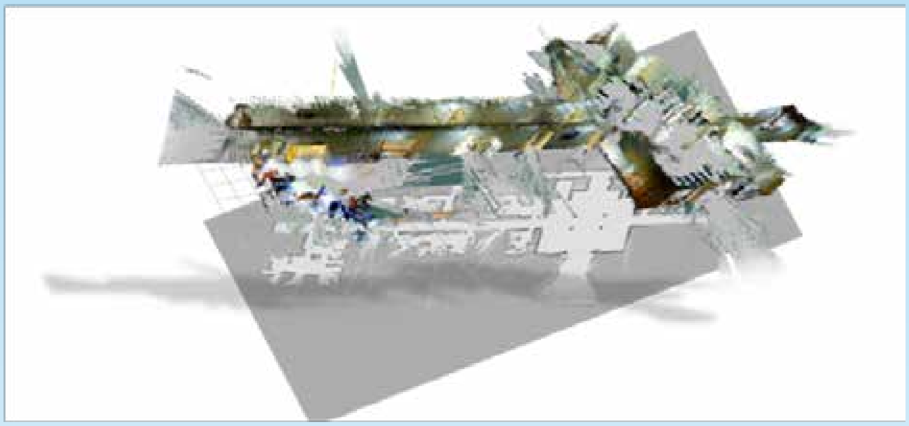
Mapping is the process of creating a map of the environment as the robot travels. Mapping enables a robot to remember the perceived changes in the environment over the temporal horizon of the operation in an existing map or in an online generated map. The change in the environment could be because of non-availability of an earlier available path, availability of a new path, change in structure and placement of elements of the operational environment, etc. In absence of memory of perceived environmental changes, a robot may exhibit undesired oscillating travel patterns.

Simultaneous Localisation and Mapping

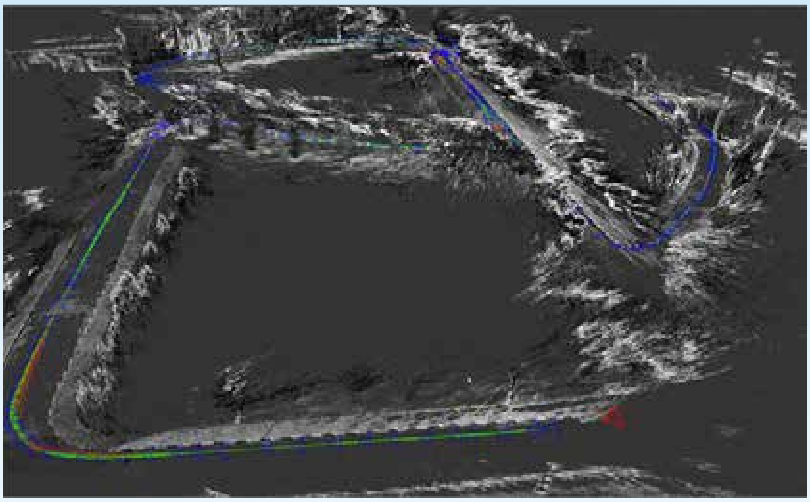
Localisation and mapping are inter-dependent activities as error in one process leads to introduction of error in another. Both these activities should be handled in conjunction. This activity is addressed using Simultaneous Localisation and Mapping (SLAM) algorithms.

SLAM is the process of creating a map of the environment while at the same time localising in the same map. A number of solutions for SLAM have been established using different sensors such as 2D and 3D LiDAR, monocular vision sensor and stereo vision sensors. The developed SLAM algorithms are based on Bayes filtering methods and Graph-based SLAM approaches. Robust sensor data processing and optimisation methods have been established. When a robot revisits a region of its environment, similarity in the sensor data are identified to correct drift errors in mapping and localisation using loop-closure algorithms. This capability has been established across multi-modal sensor data processing. The Large Scale Direct (LSD) algorithm is the state-of-the-art algorithm for estimating depth and robot pose simultaneously by minimising the photometric errors using monocular images unlike the RGBD sensor data which provides depth information. The LSD simultaneous SLAM output is shown for an outdoor and an indoor area respectively using optical sensor images. Output of 3D LiDAR based SLAM algorithm 'Laser Odometry and Mapping' on the CAIR campus is also shown. Size of the campus is approximately 350 m x 300 m.

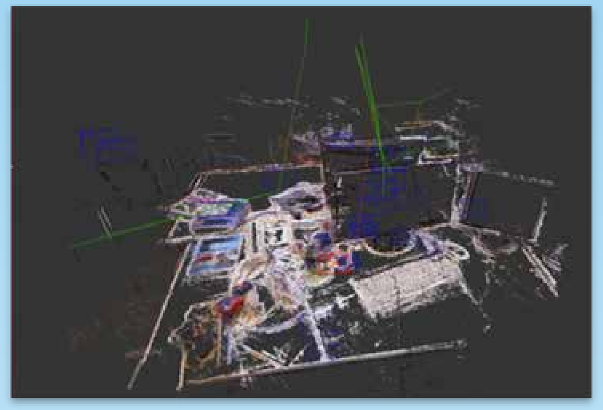
Black colour represents the ground. Increase in the height gradient is represented as a graded transition from blue to green colour. Linear lines correspond to man-made structures such as building and footpaths. Scattered clustered green colour points correspond to the trees along the road in the campus.



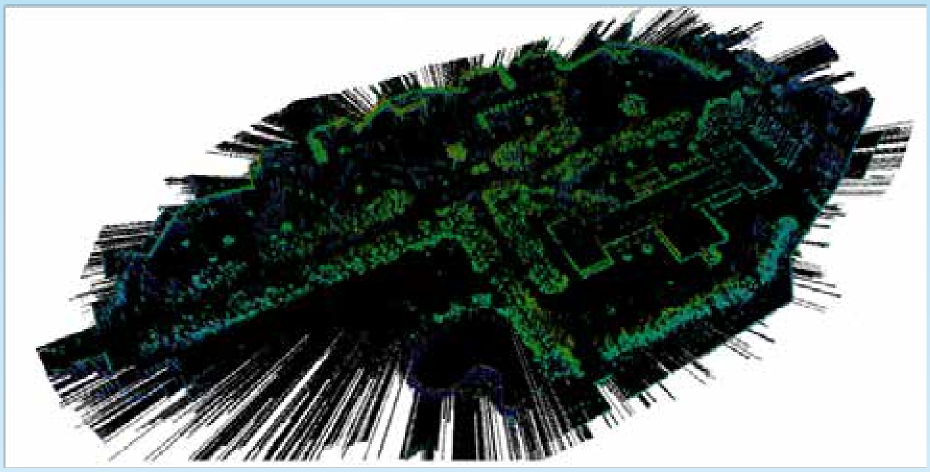
RGBD-based Simultaneous Localisation and Mapping in an Indoor Area. 3D Colour Map is Overlaid Over a 2D Occupancy Map for Ease of Visualisation



Simultaneous Localisation and Mapping in an Outdoor Area on the CAIR Campus using Large Scale Direct (LSD) Algorithm. Green Line depicts Trajectory of the Robot. Diamond Legend in Blue represents Camera Key-frame Poses. Red Line depicts the Loop Closures



Output of Large Scale Direct (LSD) Algorithm in an Office Table in an Indoor Area. Green Lines depict the Trajectory of Camera Movement. (left) A Representative Image from Robots Observations using a Payload Camera (right)



A Perspective View of an Output of 3D LiDAR Based Laser Odometry and Mapping SLAM Algorithm

Path Planning

A robot requires algorithms which enable deliberative path planning over an available map at the same time capability to perform reactive obstacle avoidance as the robot moves towards its goal. The deliberative path planner is usually known as a global planner and the reactive planner is usually known as local planner. The map for path planning is usually generated online and continuously updated using a SLAM algorithm. The path planning algorithms are based on sampling based methods and efficient state-space search. The vehicle kinematic is considered during planning stages so that the planned path is mechanically feasible for the robot to execute. Output of a 4D-state-space search based path planning algorithm across multiple floors inside a building is shown.

Exploration

In an unknown environment, a robot should decide in which direction it should explore first. Exploration algorithms detect frontiers that indicate positions where sensory information may be captured to complete the environment map or perform other intended tasks such as search for an object of interest. A frontier is a potential future direction for a

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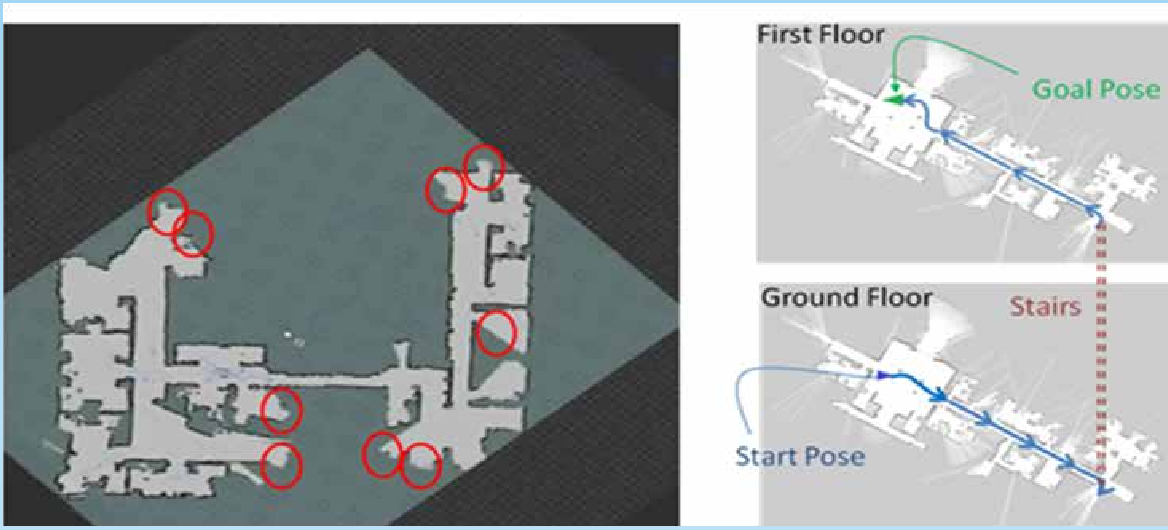

Output of Exploration Algorithm Highlighted with Red Ovals for Ease of Reference of the Reader (left). Output of a Path Planning which involves Movement across Multiple Floors in a Building (right)

robot to move. Detected frontiers by an exploration algorithm, which have been highlighted with red ovals for ease of reference of the readers are shown in figure above. The exploration algorithm chooses a frontier among various choices based on different parameters such as potential information gain on visiting a frontier, distance from current location of the robot, chances of meeting or communicating with another team member or operator, impact of travel to a new area based on uncertainty of localisation as estimated for the robot, etc.

Intelligent Mobile Robots Developed at CAIR

The various enabling technologies developed have been integrated with various intelligent mobile robots at CAIR.

Autonomous Tracked Vehicle

The Autonomous Tracked Vehicle (ATV) is a test bed for developing the Autonomous Navigation System (ANS). Perimeter surveillance of sensitive installations is one of the envisaged applications of this platform. The ATV is a commercially available Terex ST-50 tracked utility vehicle augmented with drive by wire, sensors such as LiDARs, EO/IR cameras, GPS, INS, compute hardware and a power source. Online motion control, multi-sensor data fusion, local and global path planning technologies have been developed and implemented on the ATV. The integrated technologies have been parameterised and made reconfigurable for easy porting and adaptation to similar platforms.

Autonomous Tracked Vehicle

Smart Autonomous Tracked Vehicle

The ANS established on ATV test-platform was ported to the teleoperated BMP-II developed by CVRDE, Chennai and successful summer tests were conducted at the Mahajan Field Firing Range (MFFR). The native terrain in MFFR consisted of off-road semi-arid terrain. The tests were conducted during both day and night and the vehicle was able to navigate along the given GPS way points while avoiding obstacles. The path planning algorithms were able to re-plan the path in case new obstacles were perceived along the planned path. The vehicle was operated autonomously over a total of approximately 3 kms, with the longest stretch being about 1 km. The Smart Autonomous Tracked Vehicle (SATV) employs intelligent algorithms for navigation, path planning, localisation and mapping. It processes the sensor data to perceive its environment and react accordingly. Since it is a BMP-II vehicle with armor and tracked locomotion capability, it is the most suitable unmanned robot to carry out surveillance and reconnaissance in battlefields. The user can command it to continuously patrol or reach a spot on a map, and the vehicle can autonomously navigate, avoiding obstacles on its path, until it reaches its goal.

Smart Autonomous Tracked Vehicle

Robot Sentry

Robot Sentry (RoboSen) is a mobile robot targeted at patrolling and surveillance applications in urban campuses. The system comprises an intelligent mobile robot and an Operator Control Unit (OCU), both communicating via a wireless link. Using the OCU the robot can be commanded to move autonomously along a predefined path or controlled by a joystick while providing a continuous video feedback. The RoboSen senses its environment using GPS, stabilised digital compass, and laser rangefinders which help the navigation and path planning algorithms in avoiding obstacles as it patrols a campus.

Robot Sentry

Autonomous Search Robot

The autonomous search robot can perform 3D mapping of an indoor area on its own. In addition to localisation, mapping, and path planning, it employs an exploration algorithm which searches for all unknown areas until they have been mapped. Apart from a LiDAR, it uses a RGBD sensor for 3D depth data capture. With the help of these sensors, this robot can identify 3D obstacles and avoid them during navigation. It can continuously create a 3D map of the indoor scene, which is displayed on a remote user device. The user can select an object to be searched, which are then marked by the robot when they are found in the scene. It uses algorithms for object detection to perform the search. The user can fly through the map and interactively locate searched objects in the map. The autonomous search robot is useful for indoor counter insurgency operations, search and rescue operations, and remote mapping of indoor environments with NBC hazard, when mounted with a NBC sensor.

Autonomous Search Robot

Intelligent Collaborative Robotics System

CAIR is working on developing a multi-agent robotics framework, which utilises a heterogeneous set of robots to collaboratively achieve the mission objectives. The heterogeneous platforms are connected to a Master Control Station (MCS) which collects all the mission data, maps, and live views. The wheeled robots are targeted to perform exploration outdoors, the tracked platforms are targeted towards indoor multi-floor exploration, and smaller ballbots with limited motion capability are intended as static surveillance robots, which are dropped at desired locations by the MINIUGV. The heterogeneous composition and collaboration capability lends to a myriad of military applications, such as static surveillance, indoor or outdoor mapping, search and rescue, etc. Collaboration among the heterogeneous robotic team is enabled using the MARF through a multi-layered architecture. A semantic Service Oriented Architecture (SOA) layer has been established using Java Agent Development (JADE) framework, which describes the capabilities and services on a conceptual agent level. To aid in the actual execution of the service on the robotic platform, Robot Operating System (ROS) forms the lower layer of the MARF framework.

Dependable Autonomous Unmanned Ground Vehicle

System dependability is becoming crucially important for a new generation of open, cooperative, often autonomous unmanned ground vehicles. UGVs have many potential applications and the demand for them is ever increasing. Application of UGVs ranges from military missions such as reconnaissance, surveillance and combat, industrial and search and rescue operations. In particular, based on specific mission or safety critical application scenarios, the autonomous unmanned ground vehicles should be characterised by one or more of the dependability attributes such as reliability, availability, safety, integrity, maintainability, and timeliness. The design of dependable unmanned ground vehicles is even more challenging due to aggressive advances in the technology scaling, higher frequencies and power densities that have negatively affected the reliability of the components constituting such systems. In addition, development of dependable systems by means of new software/hardware technologies for runtime adaptation to mitigate the effects of failures and to permit life time improvements is an important requirement and needs careful and rigorous consideration. The choice of system level architecture, configuration, sensors and components provide significant synergy within a robotic system. CAIR is working towards establishing dependable autonomous unmanned ground vehicles which address the key attributes of dependability.

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Editors acknowledge the contributions of Dr Dipti Deodhare, Sc G and Smt Faheema AGJ, Sc E, Centre for Artificial Intelligence & Robotics (CAIR) in preparing this issue.

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