Omni-mobility: Resilience using Wheeled and Legged Mobility
Executive Proposal Summary

Riby Abraham Boby, Jayant K. Mohanta, Suril V. Shah

November 2022

Part I

Executive Summary

Appendix A: Proposal Synopsis

Mobility is one basic requirement given the development of networked communities all over the world. Though mediums of mobility which involve land, water and air, land based systems are predominant. Wheeled mobility are predominantly used when there is convenience of good road infrastructure. But very less regions of the world can be navigated using a wheeled robot (Raibert et al., 2008). However, with the possibilities of damage to such infrastructures due to more frequent natural disasters associated with aspects like climate change, war in remote and urban centers there is a need of both alternative systems which may complement wheeled systems. Systems built with possibility of mitigating unexpected changes in external and internal environments commonly known as resilience is system which has gathered further attention after the advent of pandemic since 2019. Wheeled systems has an advantage of lesser power consumption and suitability to existing road networks. Whereas legged systems has the possibility to navigate terrains which a wheeled system may find it hard to. This project envisages building of mobility system resilient to external environments by using combination of both wheeled and legged mobility systems.

International Scenario

Mobile robots operating with some level of autonomy but teleoperated by humans were used in rovers (Fig. 1) used space explorations (NASA, 1999). However in the last decade significant development on technologies related to sensing, Artificial Intelligence and actuation systems mainly electric has lead to many demonstration of autonomous vehicles (Badue et al., 2021). Majority of the mobile robotic systems have limited autonomy and requires a human supervision given the fact that most of the self-driving cars have only reached level-2 capability only (SAE, 2021). However there are numerous instances of delivery mobile robots being used in commercial fashion designed for operation in previously charted regions with capability of avoiding obstacles and following the path set earlier (Cunnane, 2022). The pandemic has accelerated the growth of

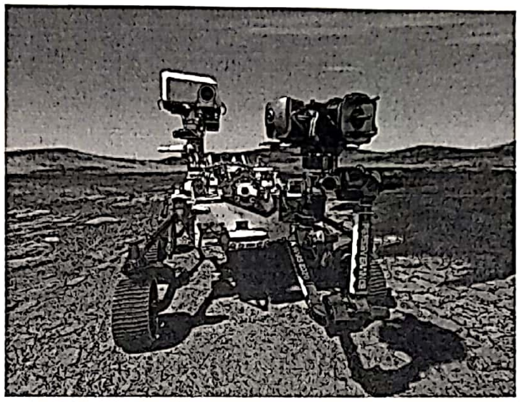
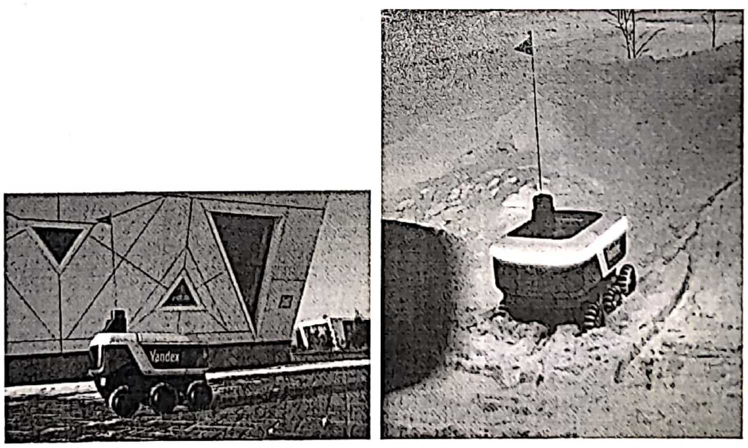


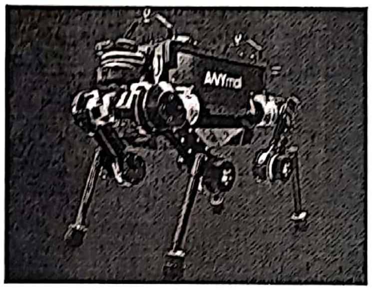
Figure 1: NASA Perseverence IEEE (2022)



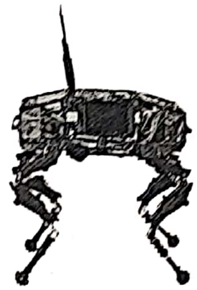
(a) Normal operating condition

(b) Wheels stuck in snow during winter

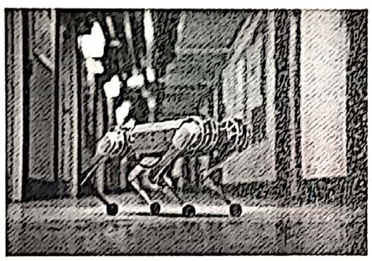
Figure 2: Failure in wheeled robot with change in climatic conditions



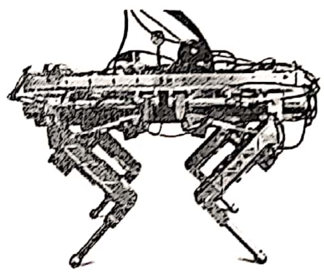
(a) ANYmal by ETH zurich



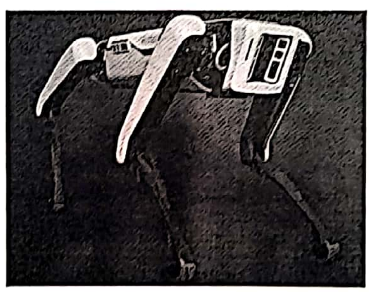
(b) Big Dog by Boston Dynamics



(c) Cheetah by MIT



(d) Hyq by IIT



(e) Spot Mini by Boston Dynamics

Figure 3: Popular quadruped robots (from IEEE (2022))

the market for such systems. All of these systems are wheeled robots and there has been significant studies into its capabilities and technology (Siegwart et al., 2011).

When it comes to legged robots the research activities have been ongoing since 1980 (Raibert et al., 1986). An initial attempt was made to simplify a pair legs with a single leg. A system was built and demonstrated based on this concept. The inability of mobile robot to navigate a major part of the earths terrain has lead to the popularity of legged robots (Kar et al., 2003). A large number of new developments that made it popular is the products from Boston Dynamics (Raibert et al., 2008). The videos of quadruped robots navigating difficult terrains and recovering from disturbances have gained very high popularity. However the legged robots have inherent issue with high energy requirement (Kar et al., 2003). The presence of a noisy Internal Combustion engine for taking care of the energy requirements had lead to the robot being noisy and therefore it could not be deployed by the United States army. With the aim of reducing the power consumption, a new class of robots with both legs as well as wheels have become popular (Krotkov et al., 1991; Bjelonic et al., 2019). This is especially suitable owing to the possibility of reducing the power consumption as well as the ability to recover functionality in difficult to navigate terrains (Fig. 2). In mission critical applications like space exploration, defense, etc. such robots will increase the robustness or resilience of the system. Figure 3 shows most popular quadrupeds.

With the increased uncertainties due to pandemic and climate change, systems resilient to external disturbances are gaining popularity. Such an approach has been proposed in manufacturing industries (Zhang and van Luttervelt, 2011). Mobile robot systems are often subject to uncertainties due to new terrains that are uneven and unexpected like those filled with sand, snow, mud, undulations, etc. It is necessary to make the robot resilient (Zhang et al., 2017b) to such environments by adding alternative methods of locomotion. It may be possible to change the configuration and use alternative systems, rather than getting stuck in a unique situation. Such approaches have been discussed in other areas of robotics (Zhang et al., 2017a). Resilience in other robotics applications have been discussed by various authors Leite et al. (2018) to tide over possibility of failure.

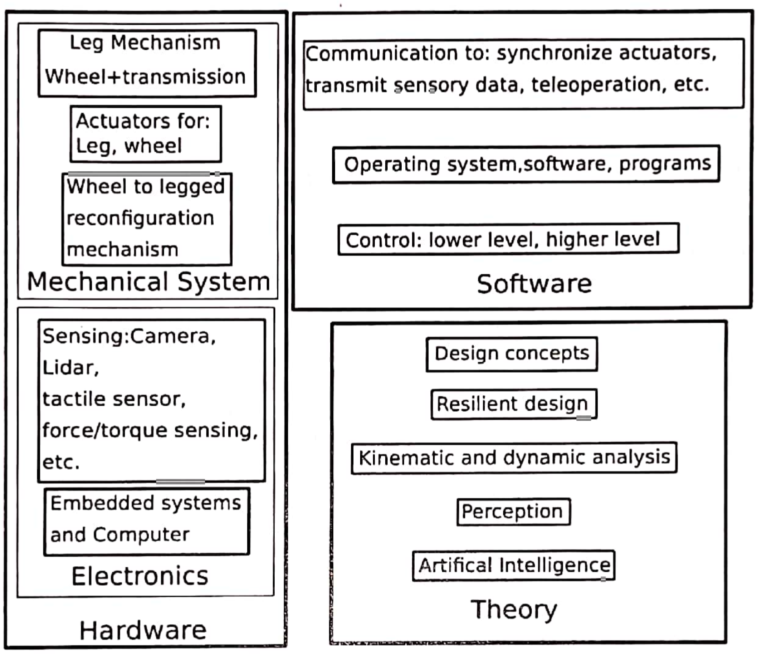
A study of resilient mobile robotic system exploiting the capability to use both legged and wheeled manipulation is not available. The current study envisages contributions in this direction.

National Scenario

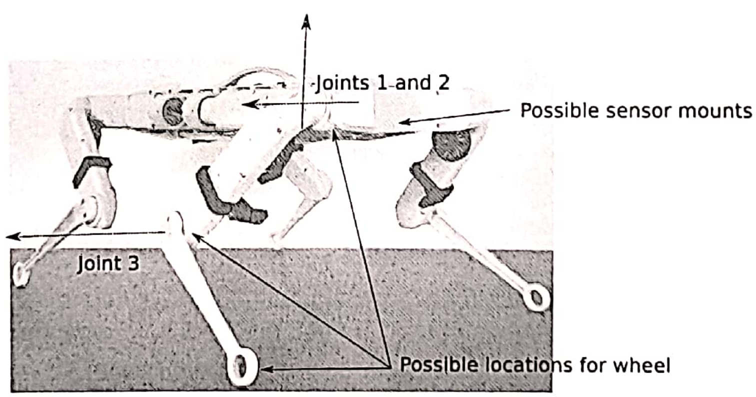
In India, DRDO labs have been actively involved in building mobile robot systems of different payload capabilities and functions, however information is not available in open platforms (DRDO, 2016). Apart from this there are companies involved in manufacturing and supply of mobile robots, and many are deployed in automating ware houses. A small sized quadruped has been demonstrated at Indian Institute of Science (IISC, 2022). Small versions have also been built by a collaborative team from IIIT Hyderabad and IIT Jodhpur (Kumar et al., 2015; Agrawal et al., 2017). Studies were conducted on different gaits using this setup as well.

Proposed work, and its impact

Based on the existing work it is proposed to build a system that is capable to navigate on different terrains by utilizing the ability to use legged and wheeled locomotion. It is envisaged that the developed system will enable to bring in resilience to unforeseen changes in terrain. Components of the proposed system is shown in Fig. 4. Plan is to focus on the development and demonstration of the indigenously manufactured and assembled system. It will leverage the existing expertise in dynamics of legged system, development of biologically inspired systems, visual perception within the broad area of mobile robotics available at Indian Institute of Technology Jodhpur. To the best of the author's knowledge such mobile robotic system with capability of legged and wheeled manipulation built with the aim of resilience to systematic failures due to terrain variation has not been studied especially in Indian context. The proposed project will aim to develop indigenous capabilities as well as skilled manpower in this area. With the sudden change in modern battlefields over the world owing to the possibility of mobile robotic systems, it will also contribute to capacity building at Indian level and will complement the initiatives taken by DRDO.



(a) Components



(b) Possible solutions as an adaptation of Grimminger et al. (2020)

Figure 4: Proposed system

Objectives / Goals & Impact

The objectives of the proposed project are as follows:

1. Study of existing designs of wheeled and legged robot and determination of its strengths and weaknesses. Determination and analysis of failure situations due to variation in terrain in simulation.

2. Experimenting using a physical model of quadruped and mobile robot for different terrains and conditions for validating the simulation data. The design presented by Grimminger et al. (2020) may be used to do manufacture or purchase quadruped robot. Already available mobile robots will be used for experiments as well.

3. Robotic systems may run into failure situations and all such scenarios are to be understood to incorporate capability for resilience. Different scenarios that may affect the robot will be considered at the initial stage. The errors in actuators or sensors will also be considered. All possible scenarios will be considered at the design stage itself in consultation with the end-user i.e., DRDO.

4. Using the experimental and simulation data to design the mechanical structure of a wheeled mobile robot with capability to use alternative legged locomotion mode using the concepts from design of resilient systems. The design may be compared based on concepts discussed by Zhang et al. (2017b) and the level of resilience will be decided based on the comparison studies. Various possibilities of configuring the legs and wheels will be studied as well before the comparison stage.

5. Selection of sensors and their fusion to enable resilience due to sensor errors. This will require a higher level control strategy to perceive environment and plan the path of the robot.

6. Simulation studies in software environment to understand the capability of the system to navigate in different terrains. To check different models and their capabilities and their shortcomings. Benchmarking will be done

with existing models that are available online (Hutter et al., 2017b). The metrics that will be studied may include energy expenditure, possibility to navigate in stable fashion across terrains, range of velocity and acceleration that will be possible, etc.

7. Use of design for manufacturing concepts to fine tune the model. Manufacturing the models that has shown promising results in simulation studies. Advise from DRDO will be sought to enable high quality manufacture of components. Apart from this, low level control using embedded systems may require dedicated electronics and corresponding codes which will be prepared.

8. Trials in real-world environments with varying terrains. Benchmark it with in-house manufactured systems made by DRDO DRDO (2016) or existing legged/wheeled using the metrics mentioned earlier.

Research Methodology/Approach

The approach/methodology may involve different parts. The are mentioned here.

Literature Search

The first step will involve searching the literature for the implementations of wheeled and legged robots and their combinations. Different designs will be analyzed on the basis of metrics used in mobile robotic systems like energy requirement, speed, ability to navigate difficult terrain, etc. Performance on a flat terrain and uniform terrain like concrete pavement will be considered as the reference.

Design and Analysis of Quadruped Robot

The first step will involve selecting the design of quadruped robot. This will be done on the basis of kinematic and dynamics analysis. ReDySim (Shah, 2022) software system developed at IIT Jodhpur will be used to analyze the dynamics. If detailed models are available analysis will be done using PyBullet Coumans (2022). After the dynamics analysis, the best performing designs will be shortlisted.

Design and Analysis of Mobile robot

The selected quadruped robot will be used to design a system with ability to use wheels as alternative mode of locomotion. This will again be evaluated using simulation softwares like PyBullet Coumans (2022). The main consideration would be the ability to navigate difficult terrains and also adaptability with the legged system.

Design and Analysis of Quadruped with configuration to Mobile robot

Search will be made to check the designs of existing systems with both wheeled and legged locomotion capabilities. The model made at ETH Zurich and that at DRDO labs will be considered. The performance of the designs will be analyzed and will be compared with the earlier design.

Prototyping

As far as possible the final designs will be prototyped using facilities available at IIT Jodhpur. The help from DRDO will also be sought in case there are difficulties. Strategy will be to build multiple prototypes with varying degrees of complexity. For initial demonstrations, 2 torque controlled actuators will be used for each leg. Additional 4 actuators, will be used for wheeled locomotion as well. A final prototype will involve and additional actuator for each leg, to enable the quadruped to navigate on difficult terrains as well. It may be possible to use concepts like Series Elastic Actuators to enable compliance while the robot is interacting with the surface. Apart from this the body may have to be built using components that ensure both least weight as well as maximum stength (Hutter et al., 2017a).

Perception for Navigation

The robotic system will require perception of external environment to ensure navigation in an easy manner. A combination of Lidar and camera can be used to ensure that the environment is perceived. Additional sensors like IMU also enable in the real-time operation of the robotic system (Hutter et al., 2017a). New sensors will require the external calibration with respect to the robot coordinate systems, and the methods discussed earlier by Roy et al. (2016); Boby (2020) can be used for this purpose. Such an input will enable in hierarchical control wherein the direction of motion and the lower level of actuation of robot extremities as well as stability considerations can be taken care of.

Resilience Considerations

The robot will be manufactured especially considering resilience concepts. There may be errors arising due to sensor or actuator operation. In case of sensors, the possible issue which may affect performance will be considered. For e.g., robot operating in dark environments, may require illumination sources, whereas in snowy environment may require alternatives to Lidar or fusion of both visual and Lidar information. Similarly special terrains may cause inability to use one or more of legs. What strategy can be used in such cases will also be decided. The concept of resilience based on (Zhang et al., 2017b).

Experimental Evaluation

The prototypes that are developed will be used run trials on 2 different kinds of terrains. One is sandy and the other is rocky with uniform sized rocks. The performance on a flat uniform surface will be used as benchmarks. The speed, energy requirement, and ability to complete the route will be the main metrics that will be measured.

Key Technological Challenges & Innovative Solutions

Some of the key challenges and possible solutions are mentioned here:

1. Designing a system that can use both legged as well as wheeled locomotion. Most of the existing systems use either of these. The design will enable mobility over large variety of terrains.

2. Deciding the configuration of the legs and wheels such that easy reconfigurability is ensured. This will also involve additional actuators, or possibility of using the existing actuators. The wheels can be mounted at the end of the robot leg, middle of it or on the main body of the robot.

3. Dynamics analysis of the robotic system in suitable physics based simulation systems to measure the speed, energy efficiency and ability to navigate obstacles.

4. Robotic systems may run into failure situations which is to be understood for incorporating resilience capability. Different scenarios that may affect the robot will be considered at the initial stage. Resilience due to the errors in actuators or sensors will be considered. All possible scenarios will be considered at the design stage itself in consultation with the end-user i.e., DRDO. The design will try to show resilient behavior in all these considerations.

5. Ability to use different gait patterns will depend upon the way the external environment is perceived. This requires suitable sensors like cameras, Lidars, IMU (for detecting change in orientation), etc. Individual measurements and fused information from the sensors may aid in better decision making capability.

6. Commonly used actuators in industrial robotics sytems use very high gear ratio and therefore it is difficult to sense the forces applied at the end-effector. However most of the actuators may not be able to provide high

torques without using high reduction ratio gear boxes. Quadruped may require high torque motors, also possibility to provide compliant behavior. Therefore selection of suitable actuators will be a challenge. Systems like Series Elastic Actuators will be attempted.

7. The design of the system to ensure both high strength and low weight will be necessary. Also there shoud be possibility to take care of the high heating of the actuators due to the force control strategy. The body as well as legs should be made using a combination of high strength, low weight systems and special systems to enable the dissipation of system heat also should be planned for.

8. Since the system is meant for use in India, it will be attempted to manufacture most of the system using indigenous systems This will allow the use of the system for defence related applications where indigenisations will be important. In addition to this skilled manpower with expertise in such applications is required. Apart from technological development, it will be a priority to build skills among a large number of people including students and industrial people.

Measurable Milestones

The milestones for the proposed project is as shown in the Table 1.

Table 1: Milestones for each 6 months duration

Duration (months)	Tasks
0-6 months	Literature Survey and simulations using in-house SDK RedySim. Discussions with DRDO to understand the specific requirements.
7-12 months	Comparison of different models from literature using simulation based on Physics based models
13-18 months	Quadruped design based on simulation results
19-24 months	Addition of wheeled system and simulation in Physics based simulator
25-30 months	Consideration of Resilience and suitable adaptations
31-36 months	Addition of sensors based on simulations
37-42 months	Finalization of materials, designs and building first prototype
43-48 months	Trials for benchmarking and performance evaluation
49-54 months	Building an updated version or refining the existing version
55-60 months	Reports, demonstrations and technology transfer to DRDO

Special Equipment/Facilities details

The following items may be purchased:

1. Direct drive motors with torque control capacity - 24 Nos.
2. Position tracking system (laser tracker or motion capture system).
3. RGB Cameras - 4 Nos
4. Lidar - 2 Nos
5. Jetson embedded computer - 2 Nos
6. Communication system, Network switches - 2 Nos
7. Battery pack - 4 Nos

Deliverables

The deliverables may include:

- Reports of work done;
- Softwares created;
- Designs of the overall system; and
- Workshops to convey the technical know how and for skill building.

Part II

Annexures

Annexure I: Scientific Importance of the Project

Based on the existing works related to wheeled and legged mobility systems it is proposed to build a system that is capable to navigate on different terrains by utilizing the ability to use both the legged and wheeled locomotion depending on the requirements. To accommodate the possibility of failures and to enable recovery from the failure state, it is envisaged that the developed system will enable to bring in resilience to unforeseen changes in terrain. It is envisaged to focus on the development and demonstration of the indigenously manufactured and assembled system. It will leverage the existing expertise in dynamics of legged system, development of biologically inspired systems, visual perception within the broad area of mobile robotics available at Indian Institute of Technology Jodhpur. To the best of our knowledge such mobile robotic system with capability of legged and wheeled manipulation built with the aim of resilience to systematic failures due to terrain variation has not been studied especially in Indian context. The proposed project will aim to develop indigenous capabilities as well as skilled manpower in this area. With the sudden change in modern battlefields over the world owing to the possibility of mobile robotic systems, it will also contribute to capacity building at Indian level and will complement the initiatives taken by DRDO.

Annexure II: Brief state of the art

Mobile robots operating with some level of autonomy but teleoperated by humans were used in rovers for space explorations (NASA, 1999). However in the last decade, significant developments in technologies related to sensing, Artificial Intelligence and actuation systems has lead to many demonstration of autonomous vehicles (Badue et al., 2021). Majority of the mobile robotic systems have limited autonomy and requires a human supervision given the fact that most of the self-driving cars have only reached level-2 capability only (SAE, 2021). However there are numerous instances of delivery mobile robots being used in commercial fashion designed for operation in previously charted regions with capability of avoiding obstacles and following the path set earlier (Cunnane, 2022). The pandemic has accelerated the growth of the market for such systems. All of these systems are wheeled robots and there has been significant studies into its capabilities and technology (Siegwart et al., 2011).

When it comes to legged robots the research activities have been ongoing since 1980 (Raibert et al., 1986). An initial attempt was made to simplify multiple legs with a single leg. A system was build and demonstrated based on this concept. The inability of mobile robot to navigate a major part of the earths terrain has lead to the popularity of legged robots (Kar et al., 2003). A large number of new developments that made it popular is the products from Boston Dynamics (Raibert et al., 2008). The videos of quadruped robots navigating difficult terrains and recovering from disturbances have gained very high popularity. However the legged robots have inherent issue with high energy requirement (Kar et al., 2003). The presence of a noisy Internal Combustion engine for taking care of the energy requirements had lead to the robot being noisy and therefore it could not be deployed by the United States army. With the aim of reducing the power consumption, a new class of robots with both legs as well as wheels have become popular (Krotkov et al., 1991; Bjelonic et al., 2019). This is especially suitable owing to the possibility of reducing the power consumption as well as the ability to recover functionality in difficult to navigate terrains. In mission critical applications like space exploration, defense, etc. such robots will increase the robustness or resilience of the system.

With the increased uncertainties due to pandemic and climate change, systems resilient to external disturbances are gaining popularity. Such an approach has been proposed in manufacturing industries (Zhang and van Luttervelt, 2011). Mobile robot systems are often subject to uncertainties due to new terrains that are uneven and unexpected like those filled with sand, snow, mud, undulations, etc. It is necessary to make the robot resilient (Zhang et al., 2017b) to such environments by adding alternative methods of locomotion. It may be possible to change the configuration and use alternative systems, rather than getting stuck in a unique situation. Such approaches have been discussed in other areas of robotics (Zhang et al., 2017a). Resilience in other robotics applications have been discussed by various authors Leite et al. (2018) to tide over possibility of failure.

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Annexure III: Competence Level/Previous Work Done in this or Related Fields

Riby Abraham Boby has worked in approaches of calibrating robotic systems. This has been applied on industrial robots, cable driven robots and Human-Machine Interfaces. The projects involving calibration was done for Bhabha Atomic Research Centre, Bombay. In addition to this he has also worked on pose measurements using cameras. These techniques could also be applied to industrial robots and other systems used in automation. The related results has been published in reputed Q1 journals like IEEE/ASME Transactions on Mechatronics, Robotics and Computer Integrated Manufacturing, Journal of Intelligent and Robotics Systems, International Journal of Advanced Manufacturing Technology, etc apart from a monograph by Springer. He will be taking care of the calibration and visual perception aspect of the proposed work apart from overall coordination.

Jayant K. Mohanta has been working on design and control of parallel robotics systems. He is also involved in medical and bio-inspired robotics. He has built practical demonstrable models of many systems. The results of the work has been published in many international journals like Mechanisms and Machine Theory, Robotics and Computer Integrated Manufacturing, etc. He will be involved in the design and manufacturing of the proposed systems.

Suril V. Shah has worked on the dynamics of legged robots since 17 years. He has authored articles in reputed journals like Mechanism and Machine Theory on this topic, in addition to other reputed journals. Apart from this he has created a SDK called ReDySim that can be used for simulating the dynamics of such systems. He has also been involved in projects supported by Indian Space Research Organization on controlling redundant robotic system for space debris manipulation. He will be involved in the dynamics simulation and performance analysis of the proposed system.

Annexure IV: Technical Plan/Methodology

The approach/methodology may involve different parts. The are mentioned here.

Literature Search

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Prototyping

As far as possible the final designs will be prototyped using facilties available at IIT Jodhpur. The help from DRDO will also be sought in case there are difficulties. Strategy will be to build multiple prototypes with varying degrees of complexity. For initial demonstrations, 2 torque controlled actuators will be used for each leg. Additional 4 actuators, will be used for wheeled locomotion as well. A final prototype will involve and additional actuator for each leg, to enable the quadruped to navigate on difficult terrains as well. It may be possible to use concepts like Series Elastic Actuators to enable compliance while the robot is interacting with the surface. Apart from this the body may have to be built using components that ensure both least weight as well as maximum stength (Hutter et al., 2017a).

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Experimental Evaluation

The prototypes that are developed will be used run trials on 2 different kinds of terrains. One is sandy and the other is rocky with uniform sized rocks. The performance on a flat uniform surface will be used as benchmarks. The speed, energy requirement, and ability to complete the route will be the main metrics that will be measured.

Annexure V: Activity Bar Chart/Milestones

The milestones for the proposed project is as shown in the Table 1 and is also illustrated in Fig. 5.

Table 2: Milestones for each 6 months duration

Duration (months)	Tasks
0-6 months	Literature Survey and simulations using in-house SDK RedySim. Discussions with DRDO to understand the specific requirements.
7-12 months	Comparison of different models from literature using simulation based on Physics based models
13-18 months	Quadruped design based on simulation results
19-24 months	Addition of wheeled system and simulation in Physics based simulator
25-30 months	Consideration of Resilience and suitable adaptations
31-36 months	Addition of sensors based on simulations
37-42 months	Finalization of materials, designs and building first prototype
43-48 months	Trials for benchmarking and performance evaluation
49-54 months	Building an updated version or refining the existing version
55-60 months	Reports, demonstrations and technology transfer to DRDO

Task/Time frame (months)	6	12	18	24	30	36	42	48	54	60
Literature Survey and simulations using in-house SDK RedySim. Discussions with DRDO to understand the specific requirements.										
Comparison of different models from literature using simulation based on Physics based models										
Quadruped design based on simulation results										
Addition of wheeled system and simulation in Physics based simulator										
Consideration of Resilience and suitable adaptations										
Addition of sensors based on simulations										
Finalization of materials, designs and building first prototype										
Trials for benchmarking and performance evaluation										
Building an updated version or refining the existing version										
Reports, demonstrations and technology transfer to DRDO										

Figure 5: Gantt chart showing the planned activity

Annexure VI: Innovation in Research Work

Mobility of robotic systems are based on wheeled and legged systems Hutter et al. (2017a). However a single approach may not be suitable for mobility over different types of terrains. This has lead to combination of both wheeled and legged systems to build robotic systems that are energy efficient, faster and able to move over large varieties of terrains. This is one of the innovation of the proposed project.

Another aspect of the proposed project is consideration of principles of resilience from the initial stage of the design. This will help in enabling the robotic system to respond to different kinds of failures either in locomotion or sensing. This is another innovation that is proposed.

Finally the aim will be to develop prototypes with active involvement of collaborators from DRDO to enable compliance with real-world scenario and end-user requirements. The startegic location of IIT Jodhpur will enable access to some of the common terrains associated with India's international border and this may be of interest to DRDO. From the Initial stage itself the type of terrains will be decided and the subsequent trials of the prototypes will be held in such environments. Effort will be made to build the system with indigenous capabilties thus developing a large group of skilled manpower who may work in these areas.

Annexure VII: Facilities available for carrying out the proposed research work

IIT Jodhpur has robotics laboratory equipped with a large range of equipments for e.g., motion capture system for internal use, Universal robot UR5 manipulator, small scale quadruped robot, mobile robots like pioneer, turtlebot, mobile manipulator, Jaco arm, etc. Three D printing facility is available for rapid prototyping.

Apart from this IIT Jodhpur has an Inter-Disciplinary Research Platform Robotics and Mobility Systems consisting of many faculties from different departments. There is also a dedicated master's programme in robotics and mobility which can give access to manpower who may contribute to the program. There also exist a section 8 company Technology Innovatin Hub: Drishti that focuses on computer vision applications. The participants of the projects are actively involved in these intiatives as well. In retrospect, IIT Jodhpur is endowed with both the skills and the initiative to contribute to the proposed project.

Annexure VIII: Additional Equipment Required

The following items may be purchased:

1. Direct drive motors with torque control capacity - 24 Nos.
2. Position tracking system (laser tracker or motion capture system).
3. RGB Cameras - 4 Nos
4. Lidar - 2 Nos
5. Jetson embedded computer - 2 Nos
6. Communication system, Network switches - 2 Nos
7. Battery pack - 4 Nos

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