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STEM Degrees: 2
STEM Participants: 4

Major Goals: We aimed to examine commercialization of the Slung Load Amplification Detector technology, through the NSF's Customer Discovery Process.

Accomplishments: 1. Our Team TOUCHDOWN completed the NSF Customer Discovery BootCamp process.
2. We conducted over 200 interviews in the specified period, coming in second of 10 teams in number of interviews.
3. We refined the Value Proposition of the technology, from Speed to Precision.
4. We progressed towards the Minimum Viable Products along two aspects: One is the software for predicting and controlling the oscillations of a slung load. The other is a modular Quad-Quad rotor prototype as a flexible approach to delivery of a range of payloads.

Training Opportunities: Participation in the National Science Foundation's Customer Discovery Boot Camp: 3 team members participated:
1. The Principal Investigator Dr. Narayanan M. Komerath, Professor
2. The Enterprise Lead Dhwanil Shukla, Graduate Research Assistant
3. The Mentor Dr. Ashish Thakker, CEO, Global Technologies.

Results Dissemination: Nothing to Report

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)
Participant: Dhwanil Shukla
Person Months Worked: 6.00
Funding Support:
Project Contribution:
International Collaboration:
International Travel:

National Academy Member: N
Other Collaborators:

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Participant: Luke Heyerdahl
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
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National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Kyle Watson
Person Months Worked: 1.00 **Funding Support:**
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International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Final Report
US Army Research Office, Project W911NF1710583
TOUCHDOWN Autonomous Slung Load Delivery System

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November 25, 2019

Contents

1 Introduction

The TOUCHDOWN project was proposed to exploit a breakthrough in the area of high-speed external load carriage by rotorcraft. The speed of vehicles carrying slung external loads is sometimes limited not by vehicle performance, but by concern that the load may become unstable and collide with the vehicle, particularly the rotors. This danger is most severe when the load has low inertia and large surface area, which typically occurs when a vehicle can fly much faster if safety could be assured. The technology called Slung Load Amplification Detector (SLAD) was developed from Army-funded basic research under the Vertical Lift Rotorcraft Centers program (BAA W911W6-11-R-0005). SLAD promised the ability for pilots to predict the evolution of slung load oscillations, several cycles of oscillation ahead. This would enable them to speed up the vehicle, slow down, or initiate measures to damp out oscillations by phase cancelling maneuvers. This could enhance the speed and safety of slung load carriage by a large margin. The proposal submitted in Fall 2017 was refined from a September 2016 submission on the same technology base. In June 2017, our team completed a 2-day National Science Foundation I-CORPS short course co-organized by Georgia Tech and U. Alabama Birmingham (UAB), at UAB. The value proposition was sharpened through 29 interviews across a wide spectrum of potential users of the service and customers of the product. This led to several pivots in the Business Model Canvas, that were reflected in the 2017 proposal.

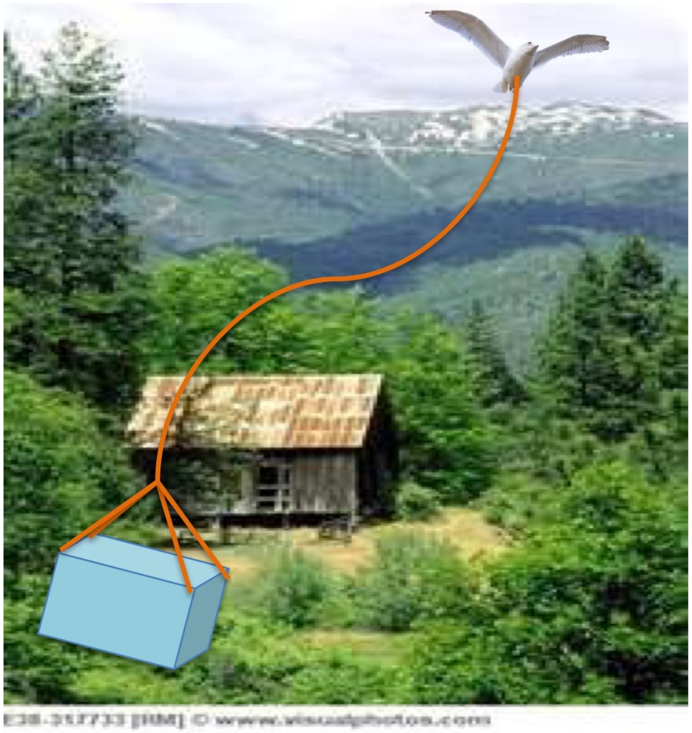

Figure 1: *TOUCHDOWN enables aerial package delivery with various vehicles.*

It is noted at the outset that this was not a traditional research project: metrics such as publications were not considered to be appropriate as the effort was to be focused on Customer Discovery using a body of basic research already completed. Technical effort was primarily on development of Minimum Viable Product demonstration: we focused on two such MVPs as explained in this report.

The project included 3 aspects:

1. Preparation and attendance in the National Science Foundation's national finals of the iCORPS Innovation Customer Discovery Boot Camp. This included a portfolio of 200-plus interviews with potential customers and industry experts including travel for in-person interviews (the NSF requirement was 100).

2. Discussions and explorations in the primary market identified in the proposal, which was deemed to be outside the NSF program as discussed below.

3. Work towards Minimum Viable Products based on the entire set of findings and future plans.

These are discussed in this report.

2 DoD Funded Basic Research Background

The basic research project titled **Unsteady Bluff Body Aeromechanics** began in 2009 under Task 9 of the Vertical Lift Rotorcraft Center of Excellence at Georgia Tech (BAA W911W6-11-R-0005). The overall Center was funded by the ARO, NASA, ONR and FAA, but all under '6.1' Basic Research. From 2011 a new Task (10) was started, with technical monitoring/mentoring from the US Army AMRDEC in Huntsville in the follow-on Rotorcraft Center grant. From 2013 through December 2016, it was continued under Task 10A, Unsteady Bluff Body Aeromechanics: Experiments and Simulation, with the technical points of contact being Dr. Tom Thompson of AMRDEC, Dr. Oliver Wong of the Army at Langley, Dr. Gloria Yamauchi of NASA, and Dr. Judah Milgram of ONR. Dr. Mahendra Bhagwat of Army AFDD is the VLRCOE coordinator. The research results are given in [1–13].

These papers trace our progress in basic knowledge from showing that 6-DOF loads at any attitude could be captured accurately and efficiently with the fine resolution needed for dynamic simulation, using our Continuous Rotation technique. This was a breakthrough by several orders of magnitude, replacing the painful, discrete-attitude measurement techniques of the past with finely-resolved, compact periodic functions. We showed that divergence speed could be predicted on-the-fly from the aerodynamic data for each model. By project end, our knowledge base exceeded 60 canonical and particular bluff body shapes (see Figure 4). We proved that in dynamic simulation with these data sets, we could capture the basic phenomena leading to divergent oscillations. We also proved a much simpler and faster simulation algorithm. The detailed aeromechanics of slung loads could be predicted on-the-fly, several cycles ahead. Proof of fidelity came when we were able to capture the detailed dynamics of two practical flight tests conducted by the military - the Engine Canister [13, 14] and the Ribbon Bridge [15], [16]. Results on the Ribbon Bridge are shown in Figure 2. As experience mounted with the large number and diversity of models, generalized prediction became realistic. The SLAD was born of experience and observations during our work on the various models, and the invention was reported to Georgia Tech Research Corporation

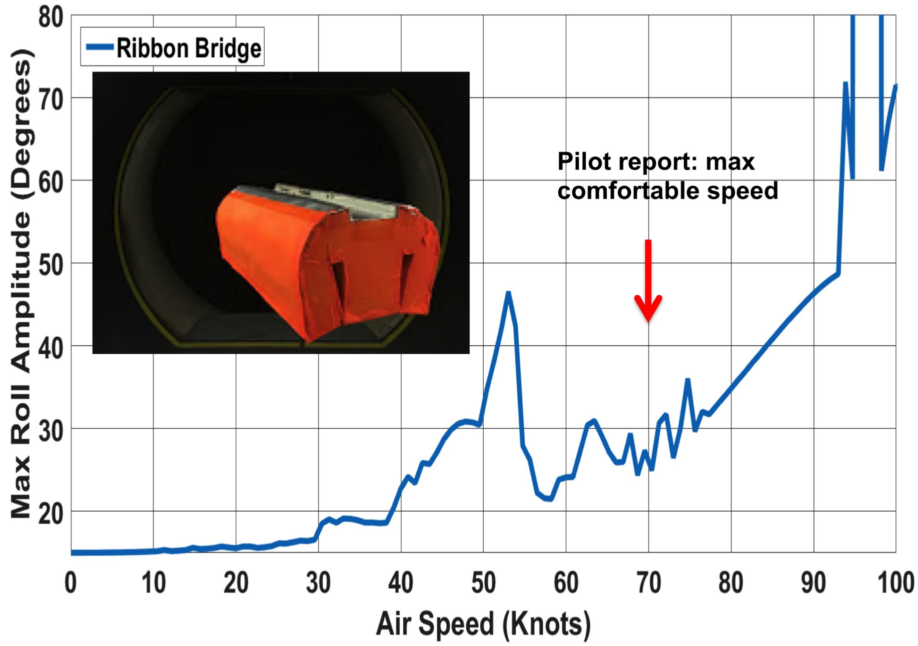

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Figure 2: *Maximum roll amplitude versus flight speed for a Ribbon Bridge model, predicted by dynamic simulation with model-scale wind tunnel aerodynamic data, compared to flight test points.*

(GTRC) in Spring 2016. Figure 3 shows the transition of our research from the 'insoluble' problem, through the basic research, across the spectrum, through the two major innovations and divergence speed simulations into the SLAD.

2.1 Implication of the Research Findings

Summarizing the above, our fundamental research in bluff-body fluid dynamics and aerodynamics broke through the barrier to capturing the aerodynamics of arbitrary-shaped bodies at arbitrary attitudes: swinging, yawing, pitching 'bluff-body' shapes such as delivery boxes and Humvees that are nothing like the streamlined, slender shapes on which most of aerodynamics research has been done. This opened the way to fast calculation of divergence speeds. Checking the results against military flight test results showed that we are capturing the dynamics at intermediate speeds well too. So we can predict the dynamics of the payload several seconds ahead of amplification, in time to take action to damp them out. This means that we can also predict precise position of the load ahead of time, enabling Point Rendezvous. Technology developed through this research is at the core of TOUCHDOWN. The initial judgement of market readiness to match technology readiness, comes

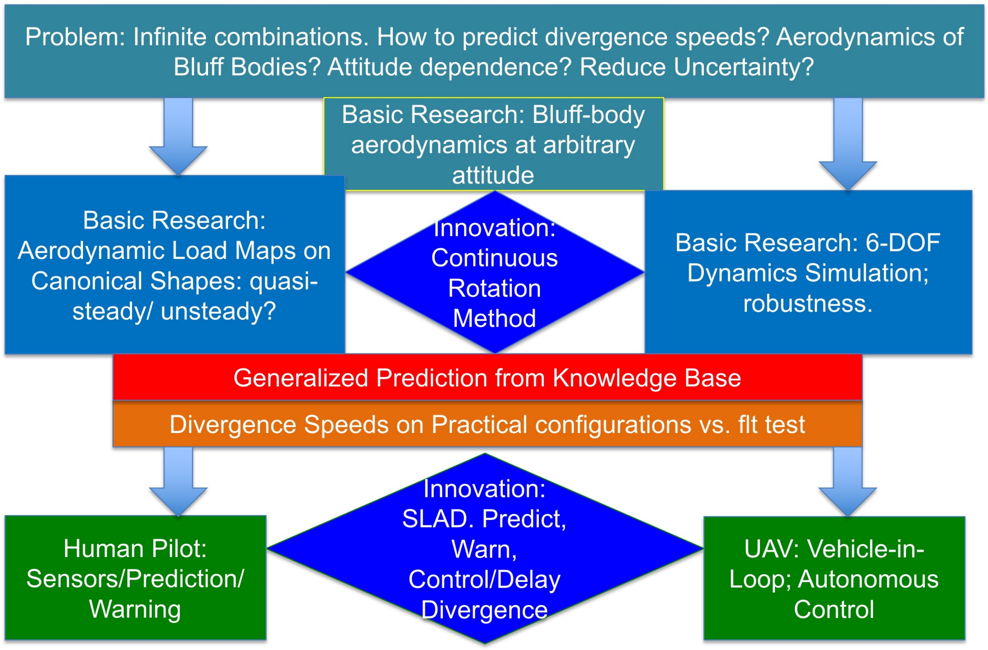

Figure 3: *The transition of the Slung Loads divergence speed prediction problem, from the red of deep uncertainty and knowledge generation through basic research to the green of the SLAD implementation proposed here. The two major enabling innovations are shown in deep blue. Dynamic simulations merged the basic research through the results from the Continuous Rotation technique, and yielded the insights that bred the SLAD invention.*

from observing several recent developments.

2.2 Initial Value Proposition: Speed

The initial value proposition was Speed. TOUCHDOWN would enable UAV manufacturers to cater to a fast-increasing and diverse market for slung-load operations. Customers would be able to receive and send products much quicker, delivered or picked up by air at their doorstep, using TOUCHDOWN as follows:

1. The military can transport slung loads 50% faster than currently permitted with assured safety, enhancing mission speed and reducing vulnerability.

2. Retail customers in areas with difficult or no road access, can slash the delivery time from the nearest transport hub by direct UAV-based delivery. The UAV does not have to land or lift off at their site, averting downwash hazards, noise and collision fears. Retail last-kilometer delivery entrepreneurs can use UAVs that cost less than their motorcycles, to deliver several times more packages than they can at present.

3. Shipping companies can increase efficiency and productivity using UAVs, cutting the

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Figure 4: *Some of the models on which aerodynamic load maps have been generated using the Continuous Rotation technique*

time for each round-trip significantly. They can also save over hub-and-spoke operations, by using UAVs directly from moving highway trucks or trains.

4. Firefighters can slash empty-bucket return times, approaching their dream of Type 1 (large aircraft) effectiveness with Type 3 (small) vehicles and cost.

5. Urban firefighters can better fight high-rise fires and rescue people.

6. Highway emergency operators can enable first responders to receive medical packages without the risk and delay of landing a UAV in clogged traffic.

7. Rescue times from rooftops in rising waters can be slashed by 30 to 50%.

8. TOUCHDOWN technology will enable Precision Point Rendezvous. This means extracting climbers stuck under mountain ledges, evacuating people from high-rise fires, and soldiers and pilots from enemy-surrounded enclaves. All without risking a human pilot or hovering over a risky area.

2.3 Market Search Beyond DoD/NASA as Per NSF Instructors

At the June 2017 NSF/GT Birmingham experience the instructors directed us to consider interviews only with potential customers outside the DoD and NASA. Most of the demand for high speed rotorcraft flight with slung loads, came from the military, so that the manufacturers of large rotorcraft typically depended on the military to specify their market and applications. The State FireWise organizations also looked to the military for technology acceptance.

Thus our first customers under the NSF Instructors' strictures, were anticipated to be UAV manufacturers who produce vehicles incorporating the TOUCHDOWN system. These manufacturers would have demand from the diverse spectrum of applications and customer types listed above. Whether essential or not for normal operations, TOUCHDOWN would multiply the market for slung-load operations.

We set out the customer segments that we expected, in the proposal submitted for the present project. The most promising markets were outside the USA, since US regulations banned the use of UAVs for retail operations in urban/populated areas, and slung load carriage by human-piloted vehicles over populated areas was also banned since safety might dictate jettisoning the load. On the other hand, it was clear that UAV-based delivery was crucial in many parts of the world that lack good road access. This includes most of the African continent, much of South and Central America and South Asia and parts of Australia and New Zealand. In these regions, prepprations for UAV operations were clearly moving ahead with urgency. Thus our anticipated customers were: Rural retail pickup/delivery by UAVs; the US DoD for large-helicopter and UAV applications, followed by US and foreign emergency response.

3 NSF iCORPS Customer Discovery BootCamp

The project required participation in the national finals of the NSF's iCORPS Innovation Customer Discovery Boot Camp in January to March 2018. Our team was called EXPAERO, based on our roots in the Experimental Aerodynamics Group at the Georgia Tech School of Aerospace Engineering. Out team was as follows (unchanged from the ARO proposal):

1. Enterprise Lead: Dhwanil Shukla, (then) PhD candidate and graduate research assistant.

2. Principal Investigator: Narayanan Komerath, Professor, School of Aerospace Engineering, Georgia Insitute of Technology

3. Entreprenurship Mentor: Ashish Thakker, CEO of Global Technologies in Atlanta.

In addition we had the mentoring from Mr. Jeff Garbers of Georgia Tech's VentureLab. His guidance proved to be crucial in negotiating the conflicting reguirements of the NSF Teaching Team versus the ARO background of our project: all other teams there were from NSF-funded research projects, very far from ARO and rotorcraft.

The Boot Camp required completing 100 valid customer interviews in 6 weeks, as well as completing various assignments on different aspects of researching the market and forming a startup venture. As dictated by the Teaching Team, these interviews did not include any with the military or NASA. These were deemed to be customers already pre-identified, but also, in the instructors' view, considered to be too slow-moving to warrant dependence for the sustenance of a start-up entity. On the other hand we were asked to ignore the clear indications of interest from India and other nations as being Future Markets that could not be the basis for a startup investment.

Of the 10 teams participating, Team TOUCHDOWN placed second, with over 200 interviews documented in the 6 week period. At the end of this exercise the recommendation from the instructor team was a "no-go" for enterprise startup. We concurred. This was based on the conclusion that present customer demand as of March 2018 was not sufficient to justify launching an enterprise as a full-time endeavor at that time. Some factors that featured are:

1. The Army had shelved further research and development in the area of Slung Loads, for a period of 5 years starting FY 2017.
2. No SBIRs had been identified that offered a path to government funding.
3. The Speed value proposition was important only to the Army; even the emergency response sector opined that speed was not sufficiently important to warrant installing a new system in rotorcraft.
4. We pivoted to the value proposition of precision and accuracy. This meant that the primary market was in developing flight simulators.
5. The market for flight simulators was deemed to be too small and narrow to enable survival of a startup entity as a supplier to the flight simulator vendors.
6. Markets outside the USA were not allowed to be considered.

3.1 Customer Discovery Summary

Table 1 and Figure 5 summarize the categories of potential customers who were interviewed, along with the number of interviews devoted to each. Each general category covers various endeavors and there is some overlap. Equipment Vendors (EV) became the most diverse category, including senior technical and businesspeople in large helicopter manufacturing companies, UAS manufacturer startup companies, and developers/ vendors of various subsystems including slung external load systems, cockpit controls, mapping systems and various other equipment. The Emergency Response (ER) category includes State FireWise Coordinators, local police and firefighters, and medical emergency workers, several of them being pilots. Helicopter Operators (HO) included large and small concerns that provide, operate

Table 1: Number of Interviews By Category

Category	**Symbol**	**Number**
Emergency Response	ER	58
Equipment Vendor	EV	60
Financial Services	FS	10
Helicopter Operator	HO	55
UAS Customer	UC	11
UAS Operator	UO	24

and maintain vehicles used in slung load operators. Financial Services (FS) includes people in the insurance and leasing industries. UAS operators include people who operate or anticipate operating UAVs, as well as airport operators who are learning to facilitate UAS operations. UAS Customers (UC) are the broad category of people who will use UAS services, as well as have to co-exist with UAS in future. This is a massive population, but due to concerns about the NSF Instructors' prejudices about limiting interviews to only those who might recommend buying our services, we limited the interviews to a very small number. This category is the most important to study in future: even the very few interviews that we dared "count", gave us very interesting and useful perspectives that fly in the face of attitudes held by UAS developers and technical people. For instance, community concerns about privacy and noise may well become the leading obstacle to UAS-based deliveries to residential neighborhoods, a prospect that is brushed off by vehicle developers and even present-day regulators! The insurance industry also appears to be quite unaware of the implications of widespread UAS operations: they still view UAS as being an Aviation Industry problem under their Aviation division. Realistically, small UAS in populated areas appears headed for insurance issues that are far more similar to those of automobile insurance, and of limited relevance to large-scale aviation systems.

3.2 Pivot in Value Proposition From Speed To Precision

The extensive and in-depth interviews above, led us to a pivot. It was clear that ONLY the military attached significant value to increased speed in external-load missions. The Emergency Services community surprised us by pointing out that the need for speed was not a pain point, even in such things as firefighting and hurricane/flood rescue. In the former, the main value of speed was that increased speed might translate into an ability to deliver significantly more water onto a fire in the early stages, rather than having to call for and wait for a large tanker aircraft. However, this was a niche application. Experienced hurricane/flood rescue pilots told us that other factors such as the hesitation of evacuees, wasted far more time than having to fly slowly with an empty bucket.

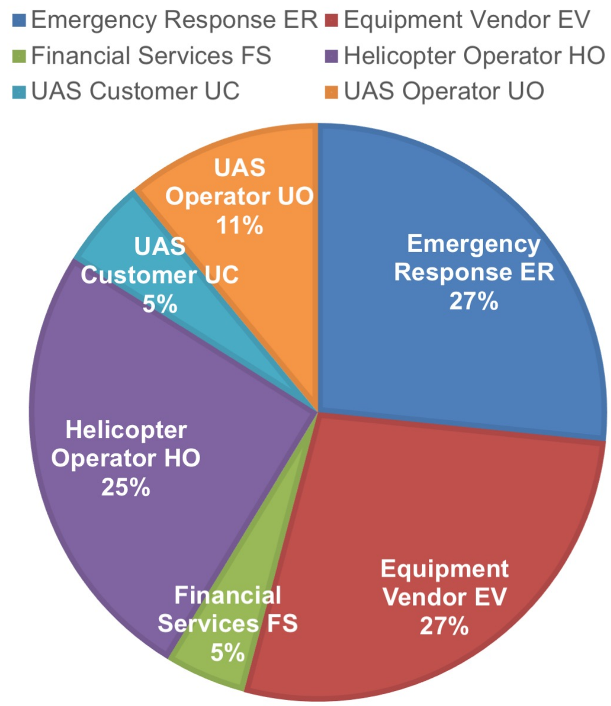

Figure 5: *Distribution of the Customer Discovery Interviews Across Categories*

On the other hand, everyone did care about improved Precision, which we could deliver. Pilot training for slung external load operations is becoming an issue, since most present pilots are Vietnam and other combat veterans, used to flying precisely and accurately by sheer experience. As these veterans retire, there is a looming shortage of firefighting and other emergency services pilots. The state of the art of slung loads simulation in flight simulators is rather rudimentary. Recent efforts in this regard are particularly revealing of the state of technology.

In this case, two avenues were identified. One is to port our software system onto Apple iPAD type devices which are now cockpit-approved. These devices could obviate the need for bubble canopies now used so that the pilot can put their helmeted head outside the nominal side window surface, and see what the slung load is doing, below.

The second avenue is to port our system into Flight Simulator modules. Both are compatible with the software development efforts that we have underway, but neither is a large enough market for a startup venture to depend upon for its initial years.

4 Other Activities

4.1 Interaction with the DoD

A presentation was made in Fall 2017 at the Army's Natick Soldier Center. Their assistance (mostly beyond the scope of this project) was sought to develop a demonstration of the SLAD technology at our wind tunnel, as prelude to developing a UAV flight demonstration. Such a demonstration, we pointed out, is key to deeper customer engagement and discovery because it will give customers a much better view of the capabilities that we want them to consider. The presentation was received well; however they pointed out that orders prohibited them from devoting any resources to slung loads development for the next fiver years. This also damped the prospects for Small Business Innovation for Research (SBIR) proposals in this area.

4.2 Customer Discovery Abroad

Several discussions were conducted during a visit to India, interacting with university, state and central government, NGOs, logistics developers, urban and rural residents to obtain a clearer view and commence partnerships towards the developing future market there. Discussions are underway with a major US-headquartered logistics company interested in testing UAVs in the Indian market. The status of those are as follows:

1. One state government told us that our technical credibility passes their initial screening. They would not assist us in forming partnerships and developing the technical plans, but once we were beyond these, we were to come back to them so that they can move ahead with facilitating the development of validated routes. They would provide the support from purchasing and from law enforcement personnel who were to be educated on the operational aspects.

2. Several universities are developing UAV systems. We anticipate collaborating with them as a knowledge integrator and provider.

3. Government and non-governmental Emergency Response organizations are also interested, particularly given the annual floods that often maroon communities and residents.

4. One prominent global package shipping company is interested in working with us.

5. Some developers of flight simulators

5 Minimum Viable Product Demonstration

Work was done along two lines towards this goal, based on the lessons learned above, and consistent with available resources.

5.1 SLAD

The first effort was towards demonstrating the Slung Load Amplification Detector technology in a product. The core software aspects were developed. Wind tunnel tests were conducted with a range of payloads to capture relevant data and experience towards a customer demonstration. This work was done with the help of a team of undergraduates in the course of Special Problems experiences (Watson, Lepez-DaSilva) under the guidance of Mr. Dhwanil Shukla, the Enterprise Lead. The team first demonstrated that the mass and the moment of inertia components of a slung payload could be measured on the fly using load cells. This is key to being able to refine the pre-estimated mass and inertia and thus improve the accuracy with which the oscillations of the load can be measured during flight. Models of the CONEX container were developed with very low inertia, in order to extend the speed range down to low levels relevant to the Precision Value Proposition, in addition to the Speed Value Proposition. An accelerometer package was built and used inside the CONEX model to track and transmit the oscillation data.

These tests were carried forward until the end of the project. Following the No-Go decision related to enterprise startup towards applications in the USA, the project timeline for commercial deployment was rearranged, back to the original one where the rural India market is seen as the first and largest market.

5.2 Quad-Quadrotor Scalable UAV

The focus was shifted to building a prototype for a scalable low-cost UAV for commercial last-kilometer delivery applications. The resulting device is the Quad-Quad UAV shown in Figure 6. This device concept achieves the desired objectives of the MVP, and is in continued refinement towards field deployment, as regulations open up. Ground (Figure 7) and flight (Figure 8)tests with individual quadrotors were conducted to calibrate the performance and interaction corrections needed for different versions of the scalable vehicle.

6 Present Status

1. In July 2019, Prof. Komerath, the Principal Investigator, chaired the First Abdul Kalam Conference at the Indian Institute of Technology, Chennai. The theme was Sustainable Development at Sustainable Cost. The prospects for UAV delivery and pickup at villages was seen to be a critical enabler of enterprise development in the 600,000 villages of India. No funds from this project were used for this activity, but

Figure 6: *Quad-quad rotor scalable UAV shown during indoor testing*

it provided a major impetus to getting visibility and buy-in from a massive customer base and government entities.

2. The Enterprise Lead, Dr. Dhwanil Shukla, graduated from Georgia Institute of Technology with a PhD in Aerospace Engineering in August 2019, and has started his career as an Assistant Professor of Aerospace Engineering at the Indian Institute of Technology, Mumbai.

3. The Principal Investigator, Dr. Narayanan Komerath, is retiring from Georgia Institute

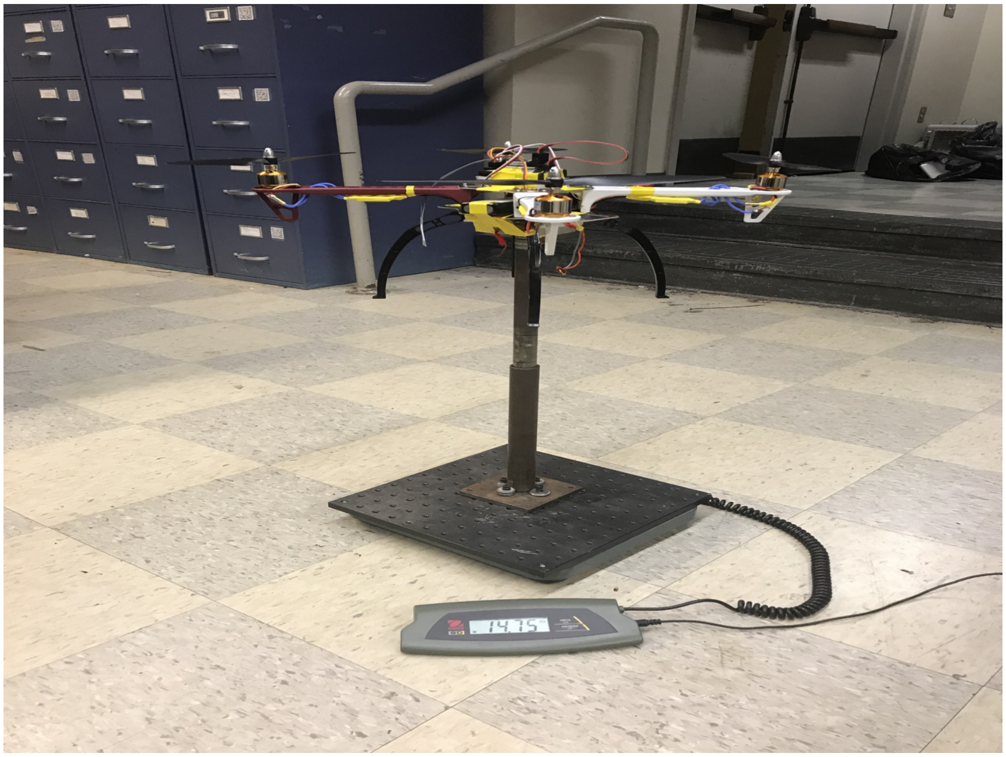

Figure 7: *Single quad rotor from the scalable UAV shown during indoor load calibration*

of Technology at the end of December 2019.

4. Current plans are to pursue development of TOUCHDOWN first in the Indian rural market. In this market we have made contacts with State authorities as well as technical, admininstrative and non-governmental organization personnel towards mentoring rural aerial delivery of small components and supplies. Contacts made through the Abdul Kalam Conference, as well as discussions in the USA, are being marshalled towards this goal.

5. The Georgia Tech Research Corporation has abandoned the SLAD Provisional Patent and thus any plans to develop the technology.

6. The Quad-quad demonstration model has been taken to flight demonstration, albeit needing further refinement of its flight control and navigation systems, as well as replacement of components with more expensive ones that exhibit better reliability than the kit parts that we used to minimize expenses.

7. Further development is being pursued in flight control augmentation. We expect to take the Quad-quad in some modified form to use in retail delivery. Several funding avenues are being developed.

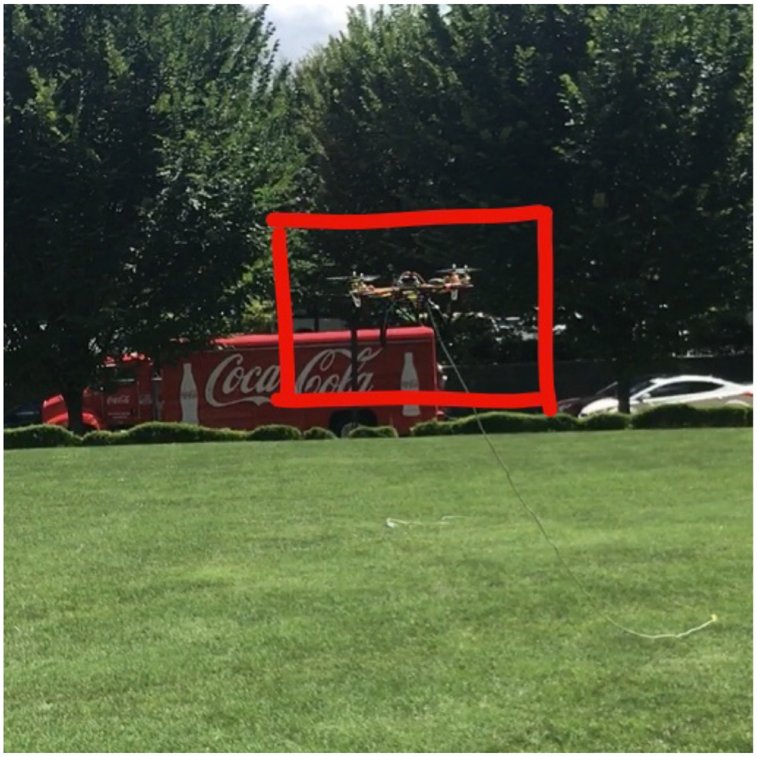

Figure 8: *Single quad rotor from the scalable UAV shown during outdoor flight testing*

8. For the immediate future our focus will be on getting some flight paths and mission profiles approved in the Indian market, building on our contacts with government and university entities, as well as local businesses.

9. One aim is to get a couple of vehicles ready before the next monsoon season, when flooding is again expected.

10. Beyond that, we plan to integrate rural UAV demonstrations into projects involving Non Governmental Organizations (US and Indian), aimed to bring energy, skills training and enterprise development to villages.

11. A pilot project in 2017-2018 has already installed solar PhotoVoltaic systems in 55 Single Teacher Schools in the state of Tamil Nadu, using village-trained installers, as the nucleus of a demonstration of geometric progression in expanding energy development.

12. In the next step this project will focus on using the energy captured in the villages, to build enterprise, with the UAVs providing a leap-frog capability to attract entrepreneurs to villages.

13. As of this writing, a feasbility demonstration project is being planned for implementation at the Enterprise Lead Dr. Dhwanil Shukla's home institution, the Indian Institute

of Technology at Mumbai.

14. Thus all capabilities learned and developed in this project are very much in use. The timeline to go into all-out commercial ventures has been extended. The original SLAD technology will still be a multiplier of capabilities as the UAV field moves into a speed-critical regime.

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