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Development of Space Robotic Force Moment Sensor

Date: November 30, 2014

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Executive Summary

A force moment sensor (FMS) informs a robot how hard it is pushing/pulling/twisting. When present, it is normally positioned between the end effector (hand) and wrist. Only a small number of robots are equipped with FMS. The terrestrial demands of FMS are significantly different that those for space. Which largely explains why the development of a space robotic force moment sensor (FMS) has been eluding the space community for 30 years. Canadarm (shuttle arm) did not have a FMS. Canadarm2 and Dextre have FMS, but reliability is problematic for operations lasting more than ½ hour. A FMS has applications in both manned and unmanned space operations.

The space environment, in combination with the operational demands for a space robot have made FMS development a difficult problem. Then there are also 'management issues'. One of the problems is that the cost and schedule for the development exceeds what engineering program managers at a single systems supplier are willing or able to invest. The second 'management issue' is the apparent simplicity of the problem.

A space FMS development demands specialization and long term commitment. It can be developed as a stand alone product, to be sold to a variety of space systems developers, or kept exclusive to a single customer. As a 'new product', expected sales had been expected to be non-existent during the multi-year development phase. Our sequence of product development is changing that. Marketing has begin with a simulator, for insertion into a robotic control test bed.

Space robots such as the Canadarms receive attention when they're in a camera equiped space arena. They move and perform counterintuitive tasks. The ability of the robotic control systems to perform constrained motion tasks is being inhibited by the lack of a space robotic FMS.

As a product, FMS represents a highly concentrated niche, for a long term product to both the human space flight and the on-orbit servicing market. It has been noted by one robotics 'guru' that space robotic FMS capability is a distinguishing feature. "Anyone can build a robot now, but ..."

The complexity of our FMS solution guarantees that production will remain with the expertise. The need for a complex solution has been validated by the number of international failures to produce an adequately functioning space robotic FMS.

The initial development costs of the FMS are substantial, for limited annual sales. The market is limitless in duration. By combining advanced marketing with simulator development, we have reduce risk and conceived a means of partially funding development with near term sales.

The 2nd version simulator (which incorporates error model of thermal influence) has just been released (www.gve.on.ca/FMS_SIM.html) .

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1.0. Good Vibrations Engineering Ltd. (GVE)

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1.1 Profile

Good Vibrations Engineering Ltd. is a privately held, Canadian company.

Sherry Draisey is owner and operator. The other staff members: Noah Mullins and Mayes Mullins.

1.2 Applicant R& D

The proposed R&D initiative is for development of a Space Robotic Force Moment Sensor. It is the continuation of development of a sensor concept, originally patented by Sherry Draisey/SPAR Aerospace in 1992.

During the 90's we received IRAP funding to build a 3 degree of freedom configuration, and some additional funding from the European Space agency to partially test it.

The originally filed patent has now expired, but substantial new IP has been developed. A provision patent was filed in 2014, just in advance of a presentation to Goddard Human Space Flight group, in January 2014. There are several advancements since the original patent. All focussed around the utilization of structural non-linearities which allow for the load transduction on the basis of frequency shift. The concept is summarized in a technical paper on our web site: www.gve.on.ca/cctomm.pdf , though it does not reflect the recent developments which are in patent process.

We began work on the 6 dof design, March 1, 2009. With funding to support hardware development, we expected a 4 year development cycle. There has been no external funding since 2009, except for small SRED payments from the Canadian Revenue Agency. In the absence of funding to support hardware procurements, we have developed designed and analyzed a 250 ft-lb version, and developed the first two versions of our on-line simulator.

We had received interest from NASA JPL on using our sensor concept as part of Mars 2020, but lack of Canadian interest and schedule constraints make that unlikely.

1.3 Need for External Investment

For many years, we considered external investment mandatory for FMS development. Then we began targeting a market pull approach. We have completed a matlab simulation of our sensor that can be built into robotic control test beds. We have also generated interest at two NASA centers. One in particular has a lot of experience with the limitations of existing space robotic force moment sensors. The is becoming a dominant player in the human space robotic industry.

The Canadian Space Agency has no interest in space robotic force moment sensing, so we have to investigate other means of funding.

A space robotic FMS represents a stable, long term product to the space sectors - civilian and defence. The FMS is a subsystem with applications in a variety of space robotic operations, with long term sales potential. The simple interface between our FMS and the systems it will be needed in (both the physical and computer interface) make it a good candidate for overcoming ITAR limitations. We have a sympathetic US defense contractor, interested in our NASA sales.

Our initial costs of the R&D and associated capital costs are substantial. One of our other products has begun to sell, and beginning to generate revenue that will allow us to slowly ramp up FMS development. But the only way we can accelerate that development time (to below 4 years) is to find an external funding source.

The nature of the FMS subsystem is such that no single systems supplier has the need to support the development of the force moment sensor. That could change, as the industry grows, and there is competition between space robotic suppliers. But for now, it is prospective sales to a wide variety of customers that warrant the initial expense (similar to aircraft landing gear - but with cleaner interface, and lower production volume). We anticipate long term annual sales of the device to be about twice the order of our initial development costs.

A Canadian company clearly has the initial advantage in selling such a device - because of our success with the Canadarms.

Until 2010, we did not have the financial resources to support our FMS development. As a result of re-sequencing our product development approach, and utilizing our existing expertise, we are actively now supporting the development organically.

We have completed the FMS simulation, on the basis of analytical modelling. The next upgrade needs to be done on the basis of some hardware testing results. Prior to ordering hardware, we will develop the design drawings of the simulated system (there have been a few design changes) and complete the ongoing patent process.

The most prohibitive cost is the test rig hardware. But we can do enough limited testing, to generate a simulation upgrade, based on modal testing results only, at a fairly modest cost.

The initial product that controls engineers need is a simulation of the FMS device - to include in their test beds. That is cheaper for us to produce, than fully tested FMS hardware.

2.0 Statement of Work

2.1 Overview of the Work

The goal of the work is the development of a pre commercial unit space robotic force moment sensor - both the hardware and software simulations of the unit. The approach to the work is parallel progress, alternating between analytical and experimentally driven development. This will allow for the demonstration of resolution capability for all 6 degrees of freedom force. The simulation product will provide customers with a low cost means of evaluating our FMS subsystem, within their system, at an early stage of their project (possibly even at their proposal stage).

2.2 Description of Major Activities and Expected Outcome

Table 2-1 presents the performance goals that the precommercial unit is to be designed to meet (and simulation shows we do meet them). Figure 2-1 provides the work breakdown structure for the plan to achieve these goals. The project schedule of section 2.3 is based on the work breakdown structure. The tasks of the WBS are defined based on the WBS. Some of tasks from WBS 110 and WBS 150 have been completed, and tasks for WBS 120 have all been completed.

Performance Characteristic	Max	Min
Measureable Force	400 N	2 N
Measureable Moment	350 Nm	1.5 Nm
Allowable Drift (10% of measurement)	8 hours	n/a
Rotational Stiffness	67.7e3 N-m/rad	35.e3 N-m/rad
Surviveable Force	600 N	n/a
Surviveable Moment	500 N-m	n/a

Figure 2-1 Work Breakdown Structure

FMS
WBS 100

B/B; 110

111. System Specification
112. System Design
113. Mechanical System
114. Microprocessor System
115. Force algorithm s/w
116. Initial Testing

Non-lin s/w; 120

121. Matlab 3 dof
122. Valid 3 dof
123. Matlab 6 dof

Pre-Com; 130

131. System Specification
132. System Design
133. Mechanical System
134. Microprocessor System
135. Force Algorithm s/w
136. Calibration Testing

Calibration; 140

141. System specification
142. System Design
143. Mechanical System
144. S/W control system
145. Neural Network Dev
146. Manufacture
147. Verification

S/W sim; 150

151. Free Version
152. B/B update
153. Pre-Com update
154. Service version

Table 2-2 Tasks for Breadboard Unit

WBS	Task Title	Task Description
110.	Breadboard Development	Extension from 3 force degree of freedom (dof) concept to 6 dof. Work to date shows that this is possible using existing 4 segment poled ceramic, but with enhanced driving approach. The frequency tracking system will use build in accelerometers. This will increase our driving system options, and improve our tracking of frequency shifts, which will lead to better force resolution.
111.	System Specification	Breadboard unit performance goals & physical configuration will be specified, for design goals and performance evaluation. **Completed**
112.	System Design	Overall mechanical, electronic and software implementation will be defined, at least in block form. This will also provide the external interface definition of the system interface to the test equipment, as well as to the larger space robotic systems it will be needed for.
113.	Mechanical System	Mechanical system consists of: housing, piezoceramic driving unit and accelerometers. The housing will be developed as drawings & sent out for manufacture. Poled ceramics already in-house will be used. Existing computer models will evaluate performance and allow some optimization.
114.	Microprocessor s/w & electronics	Existing segmentially poled piezoceramic elements will be driven with an updated electronics system to produce distinct modes shapes at the system resonant frequencies. We have developed a 3 dof driving system using a DSP, though the processing time is on the slow side. This will be modified to adequately drive each of the 6 dof's needed. We will continue to focus on driving and tracking the modes.
115.	Force Algorithm	Force algorithm is the conversion of frequency response functions to 6 dof force. We have an existing system of 3 dof prediction, but this will need to be revised to reflect the new breadboard h/w and accelerometer configuration. The accelerometers are used to monitor the frequency response of the resonances - including their amplitude. It is this combination of frequency and shape tracking that allows for the transduction to force. Measured accelerometer shapes will be aggregated to functions reflective of the loading plate shape. The force algorithm is the s/w that acquires responses and converts them into force. Algorithm will be developed in MATLAB , at the breadboard level. **Partially completed**

116.	Initial Testing	The non-linearity of the FMS is fundamental to its function. The breadboard testing will predominantly be tests to validate the unloaded structure. This information will be used to: support design changes leading to better force resolution; form the basis of a sim upgrade, for commercial sale. The frequencies will shift a bit from those predicted. The participation factors generated by the poling concept need quantification. A few, loaded configurations (mostly torsion mode) will be done to validate poling concept as adequate driving function.

Table 2-3 Tasks For Non-Linear Analysis Software Tool

WBS	Title	Task Description
120.	Non-linear, normal modes software module	A matlab routine to predict dynamic response of the structure under varying load conditions. It is a combination of partial differential equations of the 2 stiffening mechanisms involved near the strut connections, and then the knitting together of these results with special purpose FE models. This tool has 2 applications - to support the design and as an algorithm in the simulator product. **Completed**
121.	Matlab 3 dof	Matlab routine to model the stiffening nature of the system. The axial degree of freedom has been completed. The extension of this to the two moment degrees of freedom is based on the same approach - only quadrant sign changes needed. **Completed**
122.	Validate Matlab 3 dof	The routine software will be evaluated against the existing 3 dof test data available. Modification will be made as appropriate. The test data frequency shifts are based on modes high enough to avoid b.c. sensitivity. **Completed**
123.	Matlab 6 dof	3 dof s/w will be extended to full 6 dof effects. The approach should be fairly accurate for the torsion condition, but less so for the two shear directions. **Completed**.

Table 2-4 Tasks for Pre-Commercial Unit

WBS	Task Title	Task Description
130.	Pre-Commercialization Unit Development	The breadboard development will allow us to correct and refine the design to meet a generic design for a space robotic force moment sensor, suitable to the autonomous or semi-autonomous robot operations needed for satellite servicing. This may involve changes to the poling concept for the piezoceramic driving and sensing system. It will require a modified approach to securing the piezoceramic element within the housing. It will require modifications to the driving and advanced tracking system to correlate frequency shifts of multiple modes to each of the relevant degrees of freedom. It will also require significant effort to increase the speed of transduction (reduce the latency). It may also include changes suggested by users (potential customers) of our first generation simulation system.
131.	System Specification	The unit performance goals and physical configuration will be specified, to meet design goals, and for performance evaluation. This information will be made available publicly, to allow for input from potential customers
132.	System Design	The overall mechanical, electronic and software implementation will be defined. This will provide the external interface definition, in the form of ICD (interface control document) the system will interface to the space robotic systems it may be implemented in, for force moment accommodation control
133.	Mechanical System	The mechanical system will consist of a housing and a piezoceramic driving/sensing unit. These systems will be developed as drawings, to be sent out for manufacture and as computer models, to evaluate performance characteristics, to allow for some optimization within the design process. The computer models will also be used in establishing verification criteria from eventual measured test data, and to support end item calibration data sheets. The precommercialization mechanical system components will be integrated within housing. Strut tensioning conditions will be assessed.

134.	Microprocessor s/w & electronics	The piezoceramic elements will be segmentially poled, to allow for exciting various modes of the loading plate. A microprocessor and electronics system is required to drive the element segments to produce distinct mode shapes at the system resonant frequencies. The breadboard microprocessor system will be upgraded to meet performance goals. As a minimum this will involve a move to real time processing - as defined by frequency response criteria.
135.	Force Algorithm	The force algorithm will be upgraded from the b/b matlab force algorithm software that uses acquired accelerometer responses to piezoceramic oscillation and converts them into force information. This algorithm will be modified to meet mechanical characteristics of the precommercialization unit, as well as upgraded from the breadboard MATLAB software , to a faster processing language.
136.	Calibration + Thermal Testing	The non-linear function of load vs frequency will be experimentally defined, with measured data along the 6 dof forces involved, as well as influence of coupling between degrees of freedom. This testing sequence will also include thermal conditions (unit temperature changes, as well as thermal gradients across the sensor) to illustrate the sensitivity of the system to boundary condition changes. The calibration testing will be supported by a special purpose test rig. It is possible that a neural network analysis may assist in reducing the testing time needed.

Table 2-5 Tasks for Calibration Test Design & Rig

WBS	Task Title	Task Description
140.	Calibration	The calibration test rig will have 2 roles - 1st in the initial development of the non-linear sensor and 2nd as a calibrator for each sensor built The rig must be capable of allowing for fairly rapid load applications, up to fairly significant levels (safety is an issue), because the loads will have to be applied many times. A review of the potential of neural networks to minimize the number of required test sequences will be performed. The system may have to be capable of specifically applying a defined set of independent loads, as well as defined coupled loads. It will be necessary to have an accurate means of determining the load levels that are being applied. It will also be necessary to have a means of applying thermal loading conditions to the FMS unit (breadboard and pre-commercialization)
141.	System Specification	The test rig performance goals and physical configuration will be specified, for design and for performance evaluation.
142.	System Design	The overall mechanical, electronic and software implementation will be defined.
143.	Mechanical System Design & Analysis	The mechanical system will consist of a secure grounding interface, a means of quickly applying and changing out the applied loads and a means of verifying amplitude of the applied loads. These systems will be developed as drawings, to be sent out for manufacture and as computer models, to evaluate prospective performance characteristics, and to verify safety margins. The computer models may also be used in establishing verification criteria for the applied loading levels. The test rig mechanical system components will be sent out for manufacture and then be integrated. The system will be designed to allow for the addition of some simple thermal loads - either with convective or radiative means.
144.	Software & Electronics	The loads being applied may be based on physical weights, or on actuators, or a combination. A trade off of the feasibility of these options will define how much electronics will actually be needed. The software will also include a means of verifying the load level being applied to the FMS. It must also be capable of applying pure loading dof , as well as selected coupled loading dof.

145.	Neural Network Dev	The non-linear nature of the FMS makes combined loading cases particularly difficult to consider. Evaluation of the use of neural network algorithm will be performed to minimize the number of high load level tests that must be performed
146.	Manufacture & Integration	Some of the test rig mechanical system components will be sent out for machining, some will be directly procured, others produced in-house. They will be integrated in-house.
147.	Verification	Load level application verification of the test rig will be performed to validate the design.

Table 2-6 Tasks for Simulator Software Development

WBS	Title	Task Description
150.	Simulator s/w	a software system to simulate the FMS which accepts commands from a robotic control system, and provides information back to it is needed to allow customers to develop their space robotic control system, in advance of hardware implementation. It will be written in a standard language, which may or may not be platform independent. A review of elements of input and output requirements of interest to controls engineers will be undertaken.
151.	Free version	write s/w simulator that allows for simple interface to imbedded hardware that the FMS will be used in. This initial simulation will not include thermal effects, and will only be partially validated (against available test data). Place executable on web page. A 2nd version, incorporating thermal errors generated from sun on housing has been developed. **Completed**
152.	B/B update	upgrade initial simulator as b/b test data becomes available. This version will be used to support in-house consulting services related to potential FMS app's.
153.	Pre-Com Unit; update	update b/b simulator versions to reflect actual precommercialization unit test results
154.	Service Version	upgrade pre-commercial unit simulation to for sale to FMS customers

2.3 Project Schedule

Figure 2-2 is a summarized GANTT chart and Figure 2-3 provides a detailed version of current efforts.

Figure 2-2 Summarized GANTT Chart

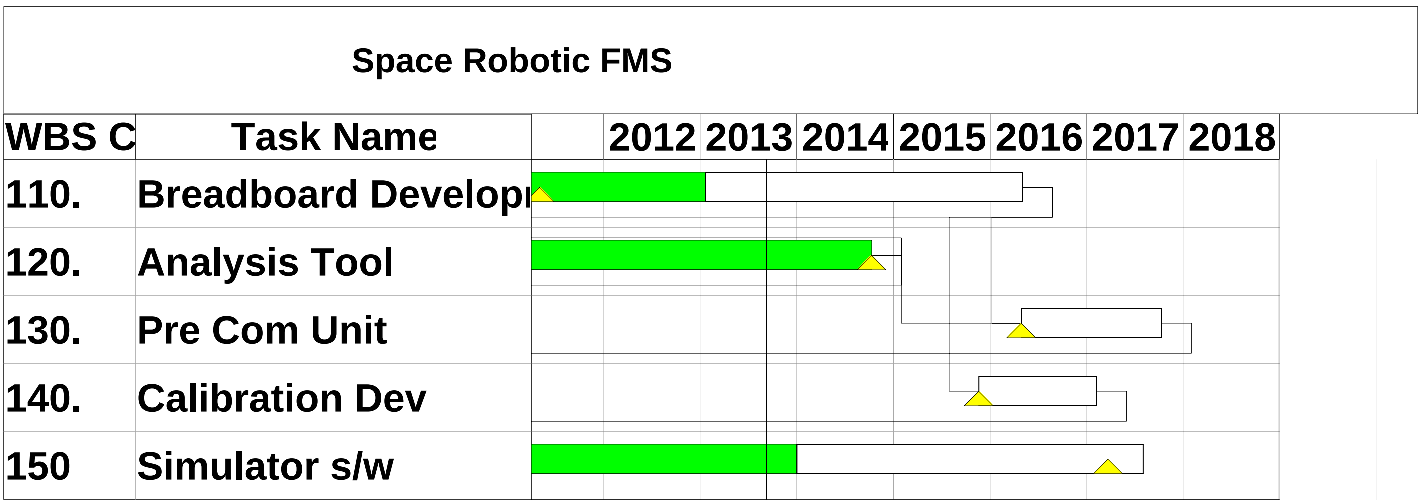
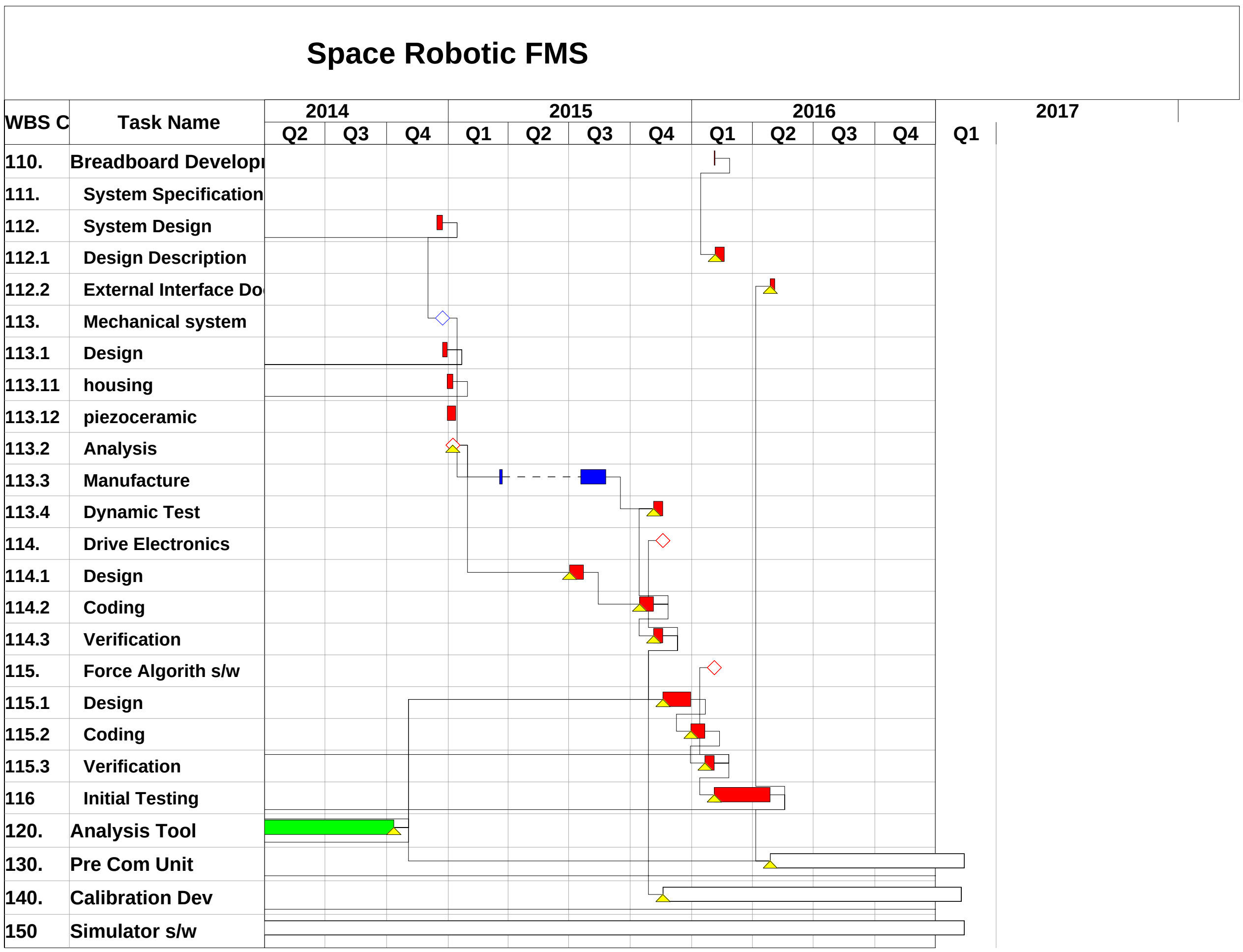


Figure 2-3 Detailed GANTT Chart



2.4 Cost Breakdown

WBS	Task	Labour	To be Completed	
			Labour	Material
110	Breadboard Unit	858,600	666,200	40,000
120	Non-linear Analysis Tool	961,920	0	0
130	Pre Commercialization Unit	932,600	932,600	17,000
140	Test Rig	705,600	705,600	300,000
150	Simulator software	1,954,200	104,000	0
	Total	$7,392,100	$2,765,400	

2.5 Anticipated Net Cash Flows by Calender Year

WBS	2014	2015	2016	2017	2018	thereafter
110		-100,000	-465,600	-140,600		
120						
130			-284,880	-664,720		
140			-1,005,600			
150	-39,600	-32,200		-32,200		
production unit				-185,000	-200,000	-400,000
unit sales					+250,000	4,000,000
SRED	8,000	11,880	47,160	526,824	251,256	
IRAP		50,000	50,000	50,000		
Sim Income			80,000	80,000	80,000	80,000
Sum	-31,600	-70,320	-1,578,920	-365,696	381,256	3,680,000

2.6 Project Location

The breadboard stage of work will be done within limited office facilities at 12585 Weston

Road, King City Ontario. The calibration rig and full range testing will need more at least a 4m x 4m x 3m dedicated lab space.

The machining efforts needed for both the test rig and the 2 FMS development units would be subcontracted out to two of the local machining groups we currently work with.

3.0 Company Capability

3.1 Management

Good Vibrations Engineering Ltd. has been combining their consulting engineering work (structural, thermal for space and geophysical developments) with in-house technology development projects since the company began operation in 1992. The company has reinvested all possible capital into development projects, all with an element of space focus. We have been ready for the space world to return interest to ISS and to an eventual Mars destination

Sherry Draisey managed 12 engineers, while she was manager of Canadian Space Station Project Structure group at the former Spar Aerospace. During the 90's, GVE's reached a staff size of 6. Sherry's long term obsession with people has resulted in a strong intelligence network in the North American space sector. It seems to play well in a sort of matchmaking between researchers, in developing the vestibulator market.

Mayes Mullins, also a former Spar employee, had a maximum staff of 90 while he was Manager of Mechanical Engineering. While Mayes is certainly capable of management of larger projects, his preference is in the technical area - and that will be his role in this project.

During the 90's Sherry also acted as a technical consultant to Canada Revenue Agency's SR&ED program - which has given her expertise in that program. In a short career, prior to engineering, Sherry's job as a pension clerk at London Life gave her a better respect for the importance of administration than is normally present in engineers.

One of Good Vibrations Engineering Ltd. management developments is our 'virtual boss'. 'He' has already focused our work to understanding of the better than expected test results from the mechanical configuration of our FMS system. Often, a boss or direct customer is needed to provide adequate motivation for difficult tasks and decisions. In the absence of such a figure, we have developed a 'virtual boss'. The concept is consistent with the 'open' applications that are unfolding. Our 'virtual boss' consists of placing the development plan on the web, and publishing a monthly report on the web (www.gve.on.ca/mth_rpt.html) , reporting progress. So far, this has been amazingly useful. We anticipate it has the additional advantage of providing a market outreach to prospective customers. We have noted about 1-2 hits a day on our monthly report - international.

3.2 Technical

Sherry and Mayes have kept abreast of technology, partially through the consulting work they perform, but also through active participation in technical conferences and technical journal.

They are both particularly capable in the project proposed;

- have extensive space robotic experience (Canadarm's), particularly in the area of structural dynamics (modal analysis).
- current geophysical consulting work is very similar in application to the test rig needed for the calibration of the FMS.
- The piezoceramic sensing element needed for the FMS is similar to a former project they developed for the DND lab in Halifax (ultrasonic destruction of micro organisms), and later applied as a project for the European space agency.
- built and tested two earlier space robotic FMS prototypes. The most successful based on the piezoceramic transduction method proposed here.
- engineering simulator developments for mechanical applications; example of 3 included on our web pages

Our proposed project is an extension of work initiated by Sherry while she worked at Spar. The patent was eventually turned over to her, after she left the company. She furthered the development of the concept through an IRAP project and subsequently with a European space agency (ESA) study. In the last five years, we have completed analysis of the ESA funded FMS test data and used it to design a 6 dof sensor. That sensor design has been analyzed and simulated in matlab. The matlab simulation is on our web page.

3.3 Financial capability

Good Vibrations Engineering Ltd. is solely owned by Sherry Draisey, and has no debt, beyond a shareholder loan (~$100,000).

3.4 Financial Status

3.4.1 Projected Financial Statements

Table 3-1 Numbers represent dollars.

	2015	2016	2017	2018	2019	2020
On-hand		115680	84120	439478	1048860	804360
Cash Receipts	28000					
Loan	100000	100000	100000			
Equity		1500000	300000	0	0	
CRA SR&ED	11880	37520	605878	284382	17500	175700
IRAP	50000	50000	50000			
Shareholder loan	38000					
Simulator Sales			80000	80000	80000	
FMS Sim Cons		25000	25000	50000	50000	
FMS Sales				250000	375000	4000000
other sales	65000	85000	85000	85000	85000	85000
	292880	1913200	1329998	1188860	1656360	5065060
Dispursements						
Long Term Debt						220000
R&D	132200	1756080	837520	50000	502000	
Marketing				20000	100000	100000
Operations	5000	48000	48000	60000	60000	100000
patent fee	25000					
Tech Consulting	10000	20000				
Manufacturing	5000	5000	5000	5000	190000	285000
	177200	1829080	890520	135000	852000	705000
Taxes	-	0	0	-0	0	-0
Ending Balance	115680	84120	439478	1048860	804360	4075060

3.5 Cost tracking / accounting system

Cost and schedule will be tracked using our Scitor Project Scheduling software.

3.6 Business plan

Our business plan is available under separate cover. It includes this project, as well as our other products and services, including our vestibulator product, which we are now exporting to the U.S and Europe.

Production of each FMS will be done with the same in-house team as is needed for this R&D exercise. Each unit will take on the order of 6 months to 1 year to produce - because of the sensitivity to calibration issues.

The unit size is quite small (< 5 kg, <1000 cm^3) so there are no significant storage challenges. Only the test rig takes up any significant space. Machining will continue to be subcontracted out locally.

Distribution issues for small size, small volume products are limited. There will be times when we package and ship with a courier, and other times when a staff member will personally deliver the device to the customer, to help with its integration.

3.6.1 Preliminary market analysis

Table 3-2 provides a preliminary market analysis of the concept. It is difficult to establish all market analysis for a product that is not yet available, and is needed by aerospace groups - they are rather secretive.

Table 3-2 Market Analysis Table

Question	Answer
Market Definition	Civilian aerospace (Canada, NASA, JAXA, ESA) American Military
Companies in the market	JR3, ATI - not suitable for space needs MDA, Motiv Space Systems - have shown interest as a partner to us
Are other companies servicing this market with similar product?	no
Is the market saturated or open?	open - no device has proved adequate yet
Market size: 1) FMS hardware 2) FMS simulator software 3) FMS simulation consulting	 1 space unit per year; 2-4 equivalent for test beds 2–5 systems per year 1-2 contracts per year
Is it a growing market?	yes - has been slowly
How do I reach this market?	internet, technical conferences, web virtual boss and matlab simulator;
How do competitors reach this market?	no competitors
What do customers expect for this product?	a proven system with clearly defined requirements
What core competencies must product have?	operate in space environment with wide range of thermal conditions. Support operations over long periods (hours, at least)
What are customers willing to pay? 1) hardware 2) FMS simulator 3) FMS Consulting	 not yet established. The 1980's demo NASA one cost $4 million net yet established - possibly $80,000 per unit probably < $50,000 per contract
What is my competitive advantage?	low drift; simulation of capabilities available free on-line

The key commercial risk is in unit pricing. Though we anticipate being the sole supplier, the cost of the technology may delay its implementation into the systems which it will support.

4.0. Benefits to Canada

4.1 Technological innovation

The challenge of solving the space robotic force moment sensor is significant, in spite of the fact that it's a product that is at least a decade overdue.

Google on 'space robotic force moment sensor' and there's lots of information of interest to Canada, on the first page. Our FMS concept paper is the 2nd hit down.

A quote from MDA about Dextre. Here's the quote:

"Probably the most important thing in Dextre is what we call the force moment sensor," explains Richard Rembala from MacDonald, Dettwiler and Associates, the renowned Canadian robotics company that has led the development of Dextre. "The sensor is located at the wrist on each arm, and this sensor really gives Dextre a sense of touch. As it's grabbing boxes, it can actually measure how hard it's pushing, how hard it's twisting. This means it can limit the forces applied to structures so it doesn't break them."

4.2 Social and economic benefits

The project we're proposing is fairly small, so the direct employment effect is small - but that employment will be long term. It is a product that will always need engineers and technicians. And it is not a product that is likely to be shipped offshore for production.

Investment returns on space products are very long term, and do not normally generate the 'hockey stick' sales curve that investors are interested in, though possibly, NASA's recent shift to private capability will change that. Either way, to continue space exploration advances, the FMS technology is one that is needed.

5.0 Loan Repayment

GVE expects to begin receiving revenue from FMS unit sales in 2018. Loan repayment will begin in 2020 and substantial dividends to investors will begin to ramp up then.