Title: , Autonomous Helicopter Navigation System, System Level, Progress Report

*“A Project”*

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**Foreword**

The progress report details the methodology, research, architectures and design for the following AHNS10 subsystems: localisation, state estimation, flight computer and communications. 4 major milestones (of which I’m responsible for) have been identified within these subsystems and must be delivered before the conclusion of the project. These include:

1. Successful communication with all sensors in the system
2. Fusion of all relevant sensor data into one estimated state representation
3. Ability to correctly measure and predict the platform’s states
4. Flight computer communication and server implementation with low CPU utilisation and low latency

Work has progressed on each of these milestones throughout semester 1. Communication interfaces for the 4 sensor devices (milestone 1) is nearing completion with a software interface library being written for the IMU and a Qt widget camera feed for the Blackfin SRV-1 camera. The remaining work left for this milestone includes the implementation of the Vicon motion capture system client and the range sensor interface library. It is anticipated that successful communication with all sensors in the system will be achieved by the commencement of semester 2. Initial research has also begun with the design and implementation of the Kalman filter (milestone 2). The Kalman filters purpose is to provide high quality state estimates for the quadrotor states. The design of the Kalman filter will conclude in the midyear semester break with an implementation of the filter ready for platform testing by semester 2.

The performance and accuracy of the sensors and filters approach will be verified and validated through the Vicon motion capture system (milestone 3). It was decided to utilise the Vicon motion capture system as a performance measuring tool due to its sub-millimetre accuracy and high update rates. A network topology has been designed and tested which allows multiple UDP clients to connect to the UDP server on the flight computer (milestone 4). The UDP server has successfully been able to use the IMU serial library to deliver the sensor data from the IMU to the GCS located on another computer. Milestone 4 will be completed once the flight computer server can control the quadrotor platform successfully which will involve reading sensors, filtering the data and updating control loops. Finally three major risks were also identified that could potentially delay and stall the project. The procedures to mitigate and reduce the risks were noted in the likelihood that they will occur.

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**Definitions**

|  |  |
| --- | --- |
| AHNS | Autonomous Helicopter Navigation System |
| QUT | Queensland University of Technology |
| HLO | High Level Objective |
| SR | System Requirement |
| GCS | Ground Control Station |
| IMU | Inertial Measurement Unit |
| Vicon | Motion capture system |
| SPI | Serial Peripheral Interface |
| UART | Universal asynchronous receiver/transmitter |
| ARCAA | Australian Research Centre for Aerospace Automation |
| FPS | Frames Per Second |
|  |  |
|  |  |
|  |  |
|  |  |
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|  |  |

# Introduction

The progress report contains the work that has been conducted on the localisation, state estimation, flight computer and communication subsystems. 4 major milestones have been identified which represent key benchmarks within the project timeframe. These milestones are based upon the high level objectives (HLOs) and the system requirements (SRs) which are detailed in [RD/1] and [RD/2]. The methodology of guaranteeing successful delivery of these milestones is based upon that of the systems engineering approach. The current methodology has enabled work to progress on all 4 of the major milestones. Current achievements in each of the milestones will be mentioned with an estimated time of completion. Finally the delays and risks which have affected the listed subsystems will also be identified with mitigation procedures for each risk noted.

## Scope

The progress on the localisation, state estimation, flight computer and communication subsystems will be the only progress mentioned in this report. The reader is encouraged to review the accompanying progress reports from the 3 other AHNS10 members for a full overview of the entire progress of the project. Similarly the risks and recommendations listed in this report are only suitable for the listed subsystems. The application of the mitigation procedures and recommendations on different subsystems or projects may yield inconsistent results.

## Background

The AHNS10 project is a 4 person project with a mission goal of achieving autonomous stability and autonomous flight of a quadrotor platform indoors. The localisation, state estimation, flight computer and communications all represent subsystems which are all critical to the overall success of the project. Applying a suitable methodology will ensure that the milestones for each of these subsystems are delivered on time. This methodology relies on the previous work conducted by AHNS09 who had a similar mission goal and platform.

# Reference Documents

## QUT Avionics Documents

|  |  |  |
| --- | --- | --- |
| RD/1 | AHNS-2010-SY-HL-001 | AHNS, High Level Objectives of |
| RD/2 | AHNS-2010-SY-SR-001 | AHNS, System Requirements of |
| RD/3 | AHNS-2010-SY-PM-001 | AHNS, Project Management Plan of |

## Non-QUT Documents

|  |  |  |
| --- | --- | --- |
| RD/a | Sensor Dynamics 6DOF IMU | Sensor Dynamics. 2009. 6 DOF INERTIAL MEASUREMENT UNIT WITH CONTINUOUS SELF DIAGNOSIS. Available: http://www.sensordynamics.cc/images/content/file/product\_linecards/1%205\_6DoF\_IMU\_v1%207.pdf (accessed June 18 2010). |

In the event of any conflict between this document and any RD referenced herein, such conflict shall be notified to Dr Luis Mejias.

In the following text, RD/x identifies referenced documents, where "x" denotes the actual document.

# S/N 06308627 Project Summary

My primary aim in the AHNS10 project is to deliver state information of the quadrotor platform to processes that required the state data for processing. The state information will be collected from numerous sensors in their raw output format and transformed into usable and accurate estimates of the quadrotor states. The quality and latency of the state information is critical where high quality data and low latency (i.e. high update rates) are required for the overall success of the project. My responsibilities of the AHNS10 project can be summarised in the table below.

Table . - Details Description of Project Roles

|  |  |
| --- | --- |
| Role | Detailed Description |
| Localisation | - Camera selection  - Software to predict platform position (including visual algorithms)  - Integration and fusion of positional data for an overall position estimate |
| State Estimation | - Implementation of software libraries and routines that can access raw sensor data  - Filtering of the raw sensor data for high quality estimates |
| GCS | - Development of a software GUI that can transport or display platform information to a platform user |
| Flight Computer | - Implementation of an onboard software architecture that can process quadrotor inputs and outputs concurrently to achieve mission goals |
| Communication | - Interface between the flight computer and various network clients |

These responsibilities centre on the milestones that are needed for project completion. The 4 major milestones that are required to meet the project aim include:

1. Successful communication with all sensors in the system
2. Fusion of all relevant sensor data into one estimated state representation
3. Ability to correctly measure and predict the platform’s states
4. Flight computer communication and server implementation with low CPU utilisation and low latency

# Methodology for Delivering Against Milestones

The primary tool for delivering against the project milestones is the use of systems engineering. A “systems engineering” focus comprises of the following steps when used on a project: definition of high level objects and system requirements, research into the relevant areas required to meet the objects, the design and testing of solutions, integration of the design into a greater system and finally delivery to the customer. Numerous iterations can occur during these steps as well to mirror the possible changes in solution design or requirements. The practical output of this process is the timeline and duration of the work packages [RD/3]. This tool is a sound method of achieving project milestones and will be adhered to at all times through the project lifecycle.

## Milestone 1

### Quadrotor states

Achieving the milestones for the project involves first choosing the specific quadrotor states that need to be measured. The following table shows which quadrotor states needs to be measured and the sensor(s) that will measure them. There are 15 distinct states in total which were identified due to either their importance in control or the ability to localise the quadrotor platform. There are 4 sensors that will be used to measure the quadrotor states which include the Inertial Measurement Unit (IMU), the Vicon Motion Capture System, the Blackin Camera and the Range Sensor.

Table . - Quadrotor platform states and the measurement sensor

|  |  |  |  |
| --- | --- | --- | --- |
| **State** | **Sensor** | **State** | **Sensor** |
| Roll rate | IMU and Vicon | Z acceleration | IMU and Vicon |
| Pitch rate | IMU and Vicon | X velocity | IMU\* and Vicon |
| Yaw rate | IMU and Vicon | Y velocity | IMU\* and Vicon |
| Roll | IMU\* and Vicon | Z velocity | IMU\* and Vicon |
| Pitch | IMU\* and Vicon | X displacement | IMU\*, Blackfin Camera and Vicon |
| Yaw | IMU\* and Vicon | Y displacement | IMU\*, Blackfin Camera and Vicon |
| X acceleration | IMU and Vicon | Z displacement | IMU\*, Range Sensor and Vicon |
| Y acceleration | IMU and Vicon |  |  |

It is important to note that states with IMU\* are measured indirectly by the IMU through various integration and filtering techniques.

Guaranteeing the delivery of the previously mentioned milestones will involve numerous interfaces to these sensors so their sensory information can be accessed. A brief description of each sensor will now follow which will include performance metrics, channels for communication with the device and a justification as to why the sensor should be used for the project.

### Inertial Measurement Unit (IMU)

The IMU which will be used for the project is the Sensory Dynamics SD755 model. The SD755 contains 3 accelerometers which measure the X, Y and Z accelerations and 3 gyroscopes which measure the phi, pitch and yaw rates . The IMU can be interfaced by either SPI or UART. SD755 specifications including relevant drift and sensitivity parameters for the accelerometers and gyroscopes can be found in the appendix. The IMU can indirectly measure the phi, pitch and yaw angles , the X, Y and Z velocities and the X, Y and Z displacements . Correctly measuring these states by the IMU will involve the use of a Kalman filter that will need to be developed. This is a high quality IMU that was inherited from AHNS 2009 and has suitable performance characteristics for the AHNS10 project.

### Vicon Motion Capture System

The Vicon motion capture system is a sensor system that can identify and track an object within a particular environment. It involves attaching reflective spheres onto an object which can be tracked by an array of IR cameras in a controlled environment. The system can track both the position and orientation of an object to sub-millimetre accuracy. The tracking data itself is captured and sent to the Vicon Tracker Program which can distribute the data to any clients that are connected to it. The clients can connect to the Vicon Tracker Program through a TCP/IP connection. The Vicon system that the AHNS10 project will be using is based at the ARCAA building located near the Brisbane airport.

The Vicon system can supply all the required state estimation measurements i.e. all of the 15 desired state values of the quadrotor. The frequency of these measurements has a maximum rate of 200Hz which is far greater than the system requirements specify. However the latency time in transporting the state data to the onboard stability control is too great. Hence the Vicon system will have two primary roles for the AHNS10 project:

* Provide a means of verifying and validating the IMU sensor data (since the Vicon system is extremely accurate)
* Provide guidance control to the platform (stability control will only rely on the sensors onboard the platform)

It is anticipated that due to IMU drift, the IMU filtering measurements (calculated onboard the platform) will need to be zeroed at regular time intervals. The Vicon system will be used for this purpose where all state estimation measurements onboard will be compared with the current state data and adjusted if too great of error is found.

### Blackfin Camera

The Surveyor SRV-1 Blackfin Camera is the onboard camera solution for the AHNS10 project. The camera utilises an analog devices processor which can perform numerous image processing tasks including edge detection, blob detection and colour segmentation. The image processing data can be accessed through the following connection types: UART, I2C and SPI. The image feed from the camera can also be accessed by a WiFi connection which is facilitated through the Lantronix Matchport 802.11 module. The Surveyor SRV-1 Blackin Camera was chosen to be the onboard camera due its recommendation from the Project supervisor and to streamline other associated projects which are also using the camera.

The original intent of the onboard camera for the project was to provide an origin for dead reckoning navigation. The origin of the system was to consist of a shape or symbol such that the quadrotor platform could utilise image processing blob techniques to localise itself within its environment (through X and Y displacements). Commands could then be issued such that robot could displace itself with respect to the shape or maintain its current displacement position in space. However with the recent inclusion of the Vicon system this functionality has been made redundant since the Vicon system can provide a much more accurate level of X and Y displacement than compared with the Blackfin camera image processing.

The Blackfin camera’s role has now been revised to perform a tracking task. It will now be used to detect a track located on the ground where the quadrotor platform will be flying. The track will be a strip of coloured material that will be identified through a combination of edge detection and colour segmentation techniques. Thus when the quadrotor platform is put into autonomous mode it can follow a pre-determined track that has been laid out which will be detected by the Blackfin camera.

### Range Sensor

The altitude or Z displacement of the quadrotor platform was to be measured primarily by a Sharp GP2Y0A710K0F. This sensor has a measurement distance of between 100-550cm. However with the inclusion of the Vicon system this sensor has also been made redundant for two reasons:

* The sensor used IR technology which would interfere with the IR cameras of the Vicon system
* The Vicon system can measure the Z displacement more accurately than the IR sensor

It has been decided to retain an altitude range sensor from a failsafe point of view i.e. if the range sensor detects that it is too close to the ground then it can send a warning signal to the onboard flight computer. The range sensor that has been selected for this task is the Maxbotix ultrasonic sensor. This sensor is an enthusiast’s favourite within the robotic community which can provide object detection between 0 to 254 inches (RD/b). The update of the distance measurement is 20Hz and the data can be accessed by either: UART (9600 baud), analogue read or via pulse width. The calculation of the Z displacement will involve some simple trigonometric calculations which will include the ultrasonic sensor reading and the roll and pitch angle.

### Sensor and state architecture

The following image depicts the sensor and state architecture for the AHNS10 project. Software interfaces need to be created for all of these devices and be tested appropriately. Thus the following interface libraries or clients need to be created to achieve milestone 1:

* IMU interface library
* Vicon client
* Blackfin camera interface library
* Range sensor interface library

## Milestone 2

The raw sensor information from each of these sensors will need to be filtered and fused together to form one estimated state representation. The filtering of the sensor data is critical since the sensory data will contain inherit noise characteristics that will need to be modelled to produce high quality state estimates. Furthermore fusion of sensor data might also have to be included since multiple estimates of the same states are being measured e.g. platform attitude by the IMU and the Vicon system.

The filtering of the sensor data will be executed onboard the quadrotor platform through the possible use of a Kalman filter. AHNS09 utilised a simple Kalman filter for their platform and was implemented through C++. However the AHNS10 project group has decided to implement the flight computer code in C only. Thus the pre-existing Kalman filter code will need to be converted to be of value to the AHNS10 project. The AHNS10 project also has a more complicated suite of sensor data due to the use of the Vicon system which is external to the quadrotor platform. Hence it has been decided that the Kalman filter should be redesigned to have the best possible chance of correct implementation in the AHNS10 project. The correct implementation of this filter will satisfy milestone 2.

## Milestone 3

Successful control of the quadrotor platform will rely on the accuracy of the state measurements. Hence a verification and validation system needs to be put into place to guarantee that the state measurements developed from the sensor fusion and filtering process is correct. To achieve this milestone, the Vicon system will be used not only as a tool for localisation data but also as a verification and validation utility. This system can measure all of the required state measurements thus all of the generated onboard state estimates can be compared with the Vicon system. A latency difference will need to be taken into consideration for this measurement as the onboard system could develop its attitude state measurements faster than the quadrotor platform (or vice versa). The system can deliver sub-millimetre accuracy and is thus suitable for achieving milestone 3.

## Milestone 4

The onboard flight computer (i.e. the Overo Fire) requires a software architecture and successful implementation for the mission goals to be achieved. The following diagram depicts the software architecture for the onboard flight computer. The implementation of this architecture will be achieved through the C programming language and is crucial for achieving milestone 4.

Another important aspect of the onboard flight computer is the ability to wirelessly interface with the flight computer from the GCS. The initial network topology was to have an Adhoc network between the quadrotor platform and the client controlling it. This topology was abandoned early in the project since the quadrotor platform could only sustain one stable Adhoc client at one time. Furthermore numerous project member laptops failed to connect to the quadrotor platform in Adhoc mode as well. Thus it was decided to have the quadrotor platform as the central server node that all clients would connect to i.e. Overo Fire’s WiFi module would run in infrastructure mode. This topology was also discarded since the Overo Fire’s WiFi module cannot be run in infrastructure mode. The current network topology is to have the quadrotor platform and all of the associate clients to connect through a wireless router. Stable and successful communication with multiple clients and the flight computer server has been achieved through this topology which can be seen in the Figure below.

## Statement of Progress Against Milestones

The following progress has been made against the 4 key milestones for the project:

### Milestone 1

Successful communication with all sensors in the system

For the IMU, a serial library has been developed that can interface with the sensor. This library can connect, disconnect, set the baud rate, read/write register values, configure the IMU access modes and collect the IMU data. A serial tester driver has also been implemented that can test whether or not the serial connection to the IMU is working. The serial library has been integrated into the flight control computer and IMU data has been successfully read and transported via the UDP server to a connected client.

Similar tests have also been performed with the Blackfin camera. The Blackfin camera has been successfully powered on and connected with the current network topology. A Qt widget has also been developed that can connect to the Blackfin Camera via a standard TCP/IP connection and requests/accepts an image. This Qt widget has been integrated successfully into the GCS GUI and has an update speed of about 10Hz. More advanced functionality has also been added to the widget which allows any Blackfin Camera commands to be sent directly from the Qt widget and a FPS counter has also been implemented. The widget can also be called multiple times to server any number of Blackfin Cameras that are connected to the network.

Work still needs to be conducted on the Vicon client and the range sensor interface library. It is anticipated that both the client and the library can be completed in a relatively short timeframe due to the wealth of implementation information available for the Vicon system and the ultrasonic range module. Thus this milestone is on track to being completed in the project timeframe.

### Milestone 2

The design and implementation of the Kalman filter still needs to be completed. Work can start to progress on this milestone after the software architecture of the flight computer, implementation of the server frame work and the interface between the sensors has been concluded. It is anticipated that this milestone will be completed before the commencement of Semester 2.

### Milestone 3

The groundwork has been placed for this milestone where the states and sensors that will measure them has already been selected. To successfully achieve this milestone, the sensor interfaces and the filter both have to be implemented and have to correctly measure and predict the platform’s states. This involves an iterative procedure where the sensor interfaces and the Kalman filter will have to be continually modified until adequate performance is acquired. The measurement of the state estimation performance will be conducted through the Vicon system. The Vicon system can track and log every state of the quadrotor platform so the performance of the filter can be analysed very closely with a high degree of accuracy. A small amount of logging code will need to be written to collect the Vicon system data when the filter performance is being tested. It is anticipated that this milestone will be completed in the second week of Semester 2.

### Milestone 4

Achieving milestone 4 involves correctly setting up the Overo Fire flight computer, establishing a WiFi connection with the flight computer via a client and the implementation of a server framework. The flight computer has been reimaged with custom programs being installed. This included the cross compilation of the GSL GNU scientific library where an inverse matrix test program was developed to assess the CPU speed of the Overo Fire. The speed of the Overo Fire was acceptable until an inversion of a 100x100 matrix started to slow down and affect the performance of the flight computer. A threaded version of the matrix inversion test program also demonstrated acceptable results and proved that threading based programs will work on the Overo Fire.

The interface for accessing the flight computer is through a 802.11 g WiFi connection through the Linksys WRTGL router. This network topology was found to be the most stable out of the topologies that were investigated which allows multiple clients to connect to the flight computer e.g. multiple SSH clients can connect to the SSH server on the flight computer with no visible latency lag visible to any of the connected clients.

Finally the basic server framework has been implemented. This framework is based off the heliconnect10 UDP server where multiple UDP clients can connect to the UDP server and receive state measurement data. Both TCP and UDP based servers were tested with the flight computer where the UDP based server was found to be more reliable. The TCP server was inadequate since if more than 2 clients are connected to the TCP server then the server would begin to block one of the clients if the state measurement update rate was too fast. The UDP server implementation has proven to be successful where IMU data has been collected and distributed by the UDP server to all connected UDP clients on the network. Work still needs to progress to complete the server framework which involves: reading the sensor data, performing filtering tasks and updating the controller PID loops. It is anticipated that this milestone will be completed by the commencement of semester 2.

## Risks

There have been a small number of unforeseen problems or delays that have faced the AHNS10 project this semester. The first of these was the decision on network topology and how the clients should connect to the flight computer. A significant amount of time was invested in attempting to implement an Adhoc connection between the flight computer and multiple clients. Eventually this topology was abandoned in favour of a router architecture where the router serves as the central node for the system and distributes data between the flight computer and connected clients. Less time and resources should have been allocated in implementing the Adhoc connection (mostly through trial and error) and the transition to the router architecture should have occurred sooner. Even though the communication link between the clients and the flight computer took longer than expected to implement, the resulting network topology is extremely stable and no errors have been encountered thus far.

Another delay was the delivery of the flight computer (Overo Fire) which took over a month to arrive in Brisbane. Little could be done to rectify this delay so different project areas were addressed in the meantime e.g. powering on and receiving images from the Blackfin Camera. Shifting our focus to different project areas meant that certain components of the project were not delayed due to the late shipment of the flight computer. When the flight computer arrived it was also discovered that it was not shipped with certain connector cables that were required for bench testing e.g. a micro A to micro B USB cable. This problem was mitigated through the purchasing of the connector cable through local sources.

There are numerous risks and possible delays that will face the localisation, state estimation, flight computer and communication subsystems in the future. These include the failure or damage of equipment and hardware (technical risk), completing project milestones and HLOs within the given timeframe (scheduling risks) and implementation of the PID controllers and filters due to time constraints (scheduling risks). The consequences of these risks all would have a major impact on the outcome of the project. However the technical risk of hardware failure has the highest probability of occurring and is thus the risk that requires the most mitigation. This mitigation will be achieved through a best industry standard approach where all hardware connections and software code will be rigorously checked and tested before implementation. A second quadrotor platform is also being proposed thus these new hardware components should be purchased as soon as possible as to replace any hardware components that could be damaged on the primary quadrotor platform.

Mitigating the scheduling risks involve the proper application of systems engineering. By allocating work packages correctly in a reasonable timeframe should see both milestones and HLOs being met before the conclusion of the project. The scheduling risk of the implementation of the controllers and filters can be reduced by appropriate research techniques since the control and filtering of a quadrotor platform has been achieved in the past. This risk can be mitigated to a greater degree by also incorporating the knowledge and advisement of the project supervisor and associated QUT academics who have experience within this field of research.

# Conclusions

Work is progressing to meet the 4 major milestones that are required to be delivered for the AHNS10 project. Communication with the 4 sensor devices (milestone 1) is nearing completion with a software interface library being written for the IMU and the Blackfin camera. The Vicon client and the ultrasonic interface library should be completed by the commencement of semester 2. Initial research has begun with the implementation of the Kalman filter to provide a good estimate of the quadrotor states (milestone 2). The implementation of the Kalman filter will proceed throughout the midyear semester break and should be completed by the commencement of semester 2.

The performance of the sensors and filter to correctly measure and predict the platform’s states (milestone 3) will be evaluated when the Kalman filter and server framework has been completed. The performance will be measured against the Vicon motion capture system which will be the verification and validation tool for the state estimation subsystem. A communication link and initial server implementation has also been conducted on the flight computer (milestone 4). This milestone will be delivered when the flight computer server has been completed (with appropriate threading) and can control the quadrotor platform successfully. Three major risks were also identified and mitigation procedures were noted for each risk if they occur.

# Lessons learnt and Recommendations

The key lesson that has been learnt through the first phase of the project lifecycle is that of the need for proper research before implementation. The few minor delays that have occurred for the communications and flight computer subsystem could have been avoided if more research was conducted on these areas instead of relying on trial and error techniques to correct issues. It is also vitally important that all equipment that is being purchased from overseas be checked before it is sent. This is to reduce the likelihood of missing the purchase of a miscellaneous component during the order procedure (e.g. connector cables). If the component is left out then another order would have to be placed with the overseas company which involves another payment in postage and handling costs (which can be extremely costly).

It is recommended that the methodology of the systems engineering process be continued to be applied to the delivery of the 4 major milestones. Current work progress is proceeding on track with successful implementation and delivery of the 4 milestones by the conclusion of the AHNS10 project at the end of semester 2.

# Appendices

## IMU Specifications

Table . - Environmental Specification for the SD755

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Min** | **Typical** | **Max** | **Unit** |
| Supply Voltage | 4.75 | 5 | 5.25 | V |
| Supply Current |  |  | 150 | mA |
| Ambient Temperature | -40 |  | 85 |  |
| Dimensions (L x W xH) |  |  | 23 x 32 x 22 | mm |

Table . - Gyroscope Specification for the SD755

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **MR1** | **MR2** | **Unit** | **Condition** |
| Measurement Range | 100 | 300 |  |  |
| Resolution | 0.0039 | 0.0156 |  | True 16 bit |
| Max. RMS noise | 0.2 | 0.3 |  | Bandwidth:  MR1: 25 Hz  MR2: 75 Hz |
| Max. zero rate bias | 0.5 | |  | Zero setting at |
| Max. temp. drift of zero rate bias | 1 | |  | Over full temp. range |
| Max. sensitivity error | 2 | |  | Over full temp. range |
| Max. linearity error, versus best fit | 0.2 | |  | Over full temp. range |

Table . - Accelerometer Specification for the SD755

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **MR1** | **MR2** | **Unit** | **Condition** |
| Measurement Range | 2 | 5 |  |  |
| Resolution | 0.002031 | 0.004062 |  | True 16 bit where |
| Max. RMS noise | 3 | 4 |  | Bandwidth:  MR1: 40 Hz  MR2: 100 Hz |
| Max. zero g at RT | 0.05 | |  | Zero setting at |
| Max. temp. drift of zero g bias | 0.06 | |  | Over full temp. range |
| Max. sensitivity error | 2.5 | |  | Over full temp. range |
| Max. linearity error, versus best fit | 0.2 | |  | Over full temp. range |