The revolutionary

The Hummingbird technology was developed by MECAL and TNO in response to the growing need for highly effective, robust and affordable vibration reduction systems. It combines new and existing technologies to significantly reduce floor vibrations and also suppress disturbances caused by machine movement, ranging from very low to high frequencies. This article discusses the basics and common concepts – with their possibilities and limitations – for (active) vibration isolation. The underlying technologies provide the context for a concise description of the Hummingbird.

• ***Bernhard Bakker and Johan van Seggelen*** •

With increasing demands in terms of accuracy and speed in modern production equipment and imaging instruments, there is a growing need for highly effective, robust and affordable vibration reduction systems. The major challenge is the need to reduce external vibration sources (mostly floor vibrations), while suppressing disturbances inflicted by the accurate equipment itself. Especially at low frequencies, most technologies currently available are not capable of effective reduction of vibrations.

The basic vibration isolation problem

Figure 1 shows a table connected to the floor via a machine frame with stiffness c_{base}. Vibrations of the table can be caused by floor vibrations, via the machine frame, and by disturbance forces acting directly on the table.
The amplitude and frequency of floor vibrations are determined by vibration sources (such as adjacent machines, traffic, etc.) and by the dynamic properties of the building (stiffness, mass, eigenfrequencies). The disturbance forces are normally caused by processes and accelerating stages mounted on the table. On this table, an accurate component, for instance a lens or another precise instrument, is mounted. The position error between this accurate component and the table is designated as Δ. This error determines the machine accuracy.

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Hummingbird technology

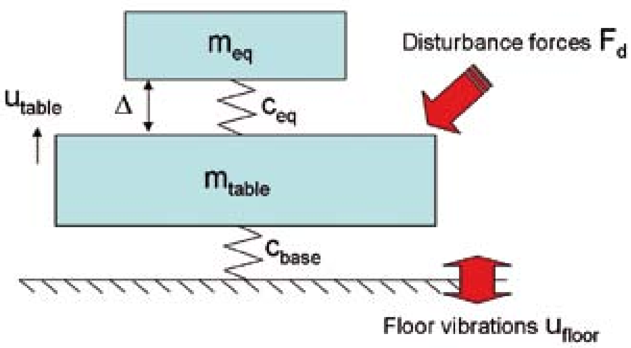

Figure 1. The basic vibration problem.

Normally, the mass of the accurate components (the equipment) on the table is much smaller than the mass of the table ($m_{eq} << m_{table}$). In that case, u_{table} is related to position error Δ through:

$$\Delta = u_{table} \cdot \left[\frac{c_{eq}}{-\omega^2 \cdot m_{eq} + c_{eq}} - 1 \right] \qquad \text{(Equation 1)}$$

This means that the error Δ is proportional to the table movement u_{table}. The challenge of vibration reduction therefore is to keep the table still in spite of the disturbance forces and floor vibrations. The effect of floor vibrations (u_{floor}) on movements of the table (u_{table}), in other words the degree of isolation of the table, is given by the transmissibility function:

$$\frac{u_{table}}{u_{floor}} = \frac{c_{base} + d_{base} \cdot j\omega}{-m_{table} \cdot \omega^2 + d_{base} \cdot j\omega + c_{base}} \qquad \text{(Equation 2)}$$

In this equation, ω is the frequency of the disturbance and c_{base} and d_{base} represent the stiffness and damping, respectively, of the table supports.

The sensitivity of the table for disturbance forces acting on the table (F_d) is given by the compliance function:

$$\frac{u_{table}}{F_d} = \frac{1}{-m_{table} \cdot \omega^2 + d_{base} \cdot j\omega + c_{base}} \qquad \text{(Equation 3)}$$

The optimum, leading to minimised table movement, is the design with minimal transmissibility (i.e. maximum isolation of floor vibrations) and minimal compliance (i.e. minimum sensitivity to disturbance forces). An important value governing both transmissibility and compliance is the eigenfrequency of the table with respect to the floor:

$$f_n = \frac{1}{2\pi} \sqrt{\frac{c_{base}}{m_{table}}} \qquad \text{(Equation 4)}$$

This frequency is in effect the cut-off frequency for the transfer of floor vibrations and disturbance forces to motion of the table: for frequencies higher than f_n the table becomes increasingly less sensitive to disturbance forces and floor vibrations. However, decreasing the stiffness between floor and table will increase the sensitivity to disturbance forces below f_n. This means that to reduce the effect of disturbance forces, the most effective way is to decrease f_n by increasing the mass of the table instead of decreasing the stiffness of the support.

Equations 2 and 3 show that around f_n both compliance and transmissibility become very high for low values of d_{base}. This means that a high damping is needed to prevent amplification of vibrations around eigenfrequency f_n. However, for higher frequencies the transmissibility increases with d_{base}, which means that low damping is needed for optimal isolation at high frequencies.

The error Δ is also decreased by minimising the mass m_{eq} and maximising the stiffness c_{eq} of accurate objects mounted on the table. This is an important part of the design of the machine itself and not part of the vibration reduction issue; therefore, it is outside the scope of this article.

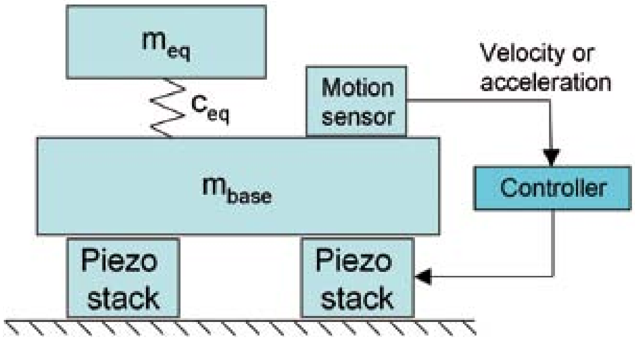

Figure 2. Piezo-based active vibration isolation.

Passive isolation

A first concept for vibration reduction is passive isolation, which means that no active components, such as sensors and actuators, are used. To minimize both compliance and transmissibility, these systems normally consist of a heavy table, as a basis for the accurate process, supported with reasonably soft supports with high damping. This means a low eigenfrequency f_n, resulting from a high mass m_{table} and a low support stiffness c_{base}.

In practice, these numbers are limited. First, the allowable mass of the table is limited for practical reasons. Second, in order to function properly, any application must be robust enough to handle a certain degree of disturbance forces, which means that the stiffness of the table supports can not be decreased too much. In practice, stable supports with a frequency lower than about 2-3 Hz are very difficult to design without active components.

An example: a 100 kg table at 2 Hz. A small force of 10 N (= 1% of the gravity force acting on the table) will already induce a displacement of 0.6 mm. In practice this means that the table is very sensitive to drift and 'feels' very unstable to the user.

High damping is needed to prevent the amplification of floor vibrations and disturbance forces at frequencies close to the eigenfrequency, but it reduces the isolation performance at higher frequencies.
Overall, passive vibration isolation is a very straightforward technology and can be effective to solve vibration issues for frequencies higher than 3-5 Hz, where a modest reduction of amplitude is sufficient.

Active isolation

If a reduction of floor vibration amplitude with a factor 2 or more at 3 Hz is required, passive isolation will be insufficient. In that case active vibration isolation can be used. This means that sensors and actuators are used to measure and counter vibrations, often in combination with a passive isolation system. Today, various solutions for active vibration isolation (or reduction) are based on three concepts as discussed below.

Piezo solutions

In a piezo actuator system (Figure 2), motion sensors are used to measure vibrations of the table. The table is mounted on stiff piezo actuators that are used to counter these vibrations. A motion controller interprets the motion sensor output and calculates the optimal counter forces.

In most piezo systems there is no passive isolation whatsoever. Therefore, the compliance is determined by the stiffness of the piezo support. This yields a very low compliance compared to other solutions. As there is no passive isolation, the reduction of floor vibrations is provided in the frequency range where the controller is active. The lower boundary of this range is determined by the resolution and noise of the sensors, the upper boundary by the controller bandwidth.

A high controller bandwidth is therefore essential. To enable this, sensors must be used with good performance at high frequencies (> 100 Hz), such as accelerometers or specific geophones. The penalty is that these sensors do not have low sensor noise and good resolution at low frequencies, e.g. below 5 to 10 Hz. Sensor noise easily exceeds floor vibrations, causing the controller to increase the vibration level rather than reduce it. Therefore, it is very difficult to reduce vibrations at low frequencies using a piezo system.
In some commercially available configurations, passive isolation is added between the piezo mounts and the supported table. In effect a table with passive isolation is mounted on top of the piezo mounts. In this way the isolation performance is enhanced at higher frequencies, but the compliance is limited by the passive system.

Note that, because of the stiff connection between table and floor, the controller bandwidth can be limited by floor dynamics. This means that for an effective piezo solution a very rigid floor is needed.

Separate reference mass

In the solution of Figure 3, a reference mass is suspended separately from the isolated table. Sensors measure the displacements of the isolated table relative to the reference mass. The controller forces the table to copy the movements (or lack thereof) of the reference mass.

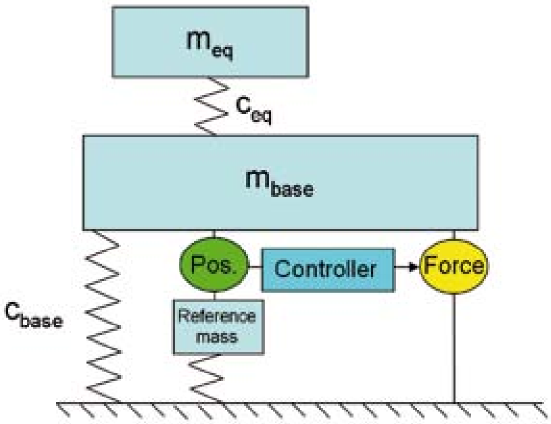

Figure 3. Active vibration isolation based on a separate reference mass.

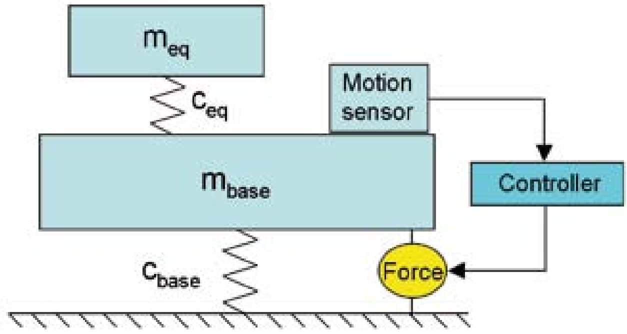

Figure 4. Active vibration isolation based on inertial control.

The basis of this concept is that the reference mass is suspended with a passive support having very low stiffness. This means that the transmissibility of floor vibrations to the reference mass is very low. The major disadvantage of passive isolation, namely the sensitivity to disturbance forces, is not a problem, because the process forces act on the table, not on the reference mass.

Note that amplification of floor vibrations to motion of the reference mass will occur around the natural frequency of the reference mass system. This is directly transferred by the controller to table motion. Considerable damping of the reference mass suspension is therefore essential.

In this design the table is supported with a 'classic' passive isolation system at a reasonably low frequency. The compliance of the passive isolation system can be greatly enhanced between 0 Hz and the controller bandwidth. For higher frequencies, the characteristics of the passive table supports apply. This means that with this concept passive isolation can be applied in situations with large disturbance forces acting on the table.
An important aspect of this solution is that vibration isolation is impossible below the natural frequency of the reference mass on its suspension (e.g. a 2.5 Hz support). Below this frequency, the amplitude and phase of reference mass movement are (almost) equal to those of the floor vibrations. Hence, in this case the controller will force the table to copy floor vibrations.

Inertial control

The basis of the inertial control configuration (Figure 4) is a table suspended by passive isolators. A motion controller is used to minimize motion of the table; actuators between the floor and the suspended table are used to counter table vibrations measured with the motion sensors attached to the table.

Compared to passive isolation, compliance and transmissibility are significantly reduced in the frequency range where the controller is active. The upper boundary of this range is determined by the controller bandwidth, and the lower end is determined by the resolution and noise level of the sensors: higher resolution and lower noise means this boundary can be close to 0 Hz, but never at 0 Hz, because then no motion occurs. Furthermore, sensors that are designed to measure horizontal motion at frequencies below 1 Hz, suffer from the 'tilt-to-horizontal coupling' effect. In short, because of gravity, the sensors cannot distinguish tilt from horizontal motion at low frequencies. This effect will be explained below.

The controller will delete the amplification of floor vibrations around the eigenfrequency of the suspension. Therefore, damping of the passive suspension is not necessary. For frequencies higher than the controller bandwidth, the vibration isolation is determined by the passive isolation system, with low damping, and therefore still is considerable.

The major disadvantage is that systems based on inertial control are sensitive to disturbance forces with low-frequency content. For static forces (0 Hz) active levelling can be added. The levelling will react to disturbance forces in the frequency range between 0 Hz and the lowest frequency at which the inertial controller is active. In principle such a levelling system is slow to react and has a reasonably high compliance.

Hummingbird technology

The Hummingbird vibration isolation technology is an enhanced version of the inertial control concept. In existing inertial control systems the motion of the table is measured with geophones or accelerometers. In the Hummingbird concept, motion of the table is determined by measuring position changes between the table and a reference mass that is suspended on the table. This technology is patented.

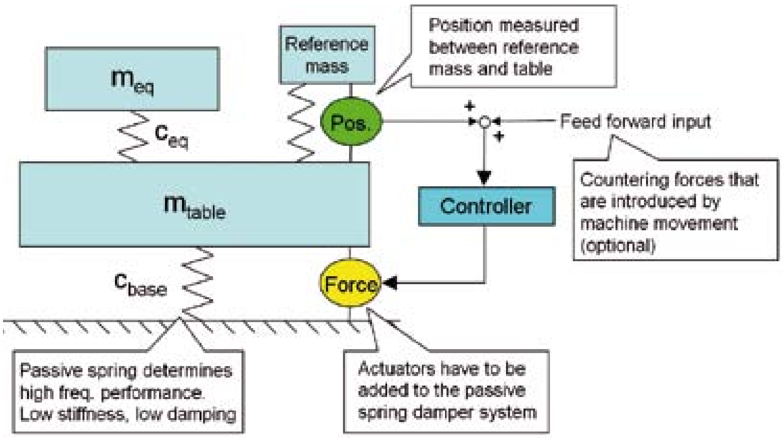

Figure 5. Hummingbird vibration isolation technology, in one DoF.

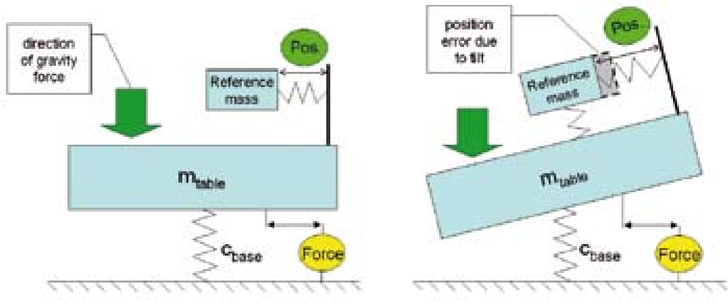

Figure 6. The tilt-to-horizontal-coupling problem in inertial control systems using reference mass-based motion sensors.

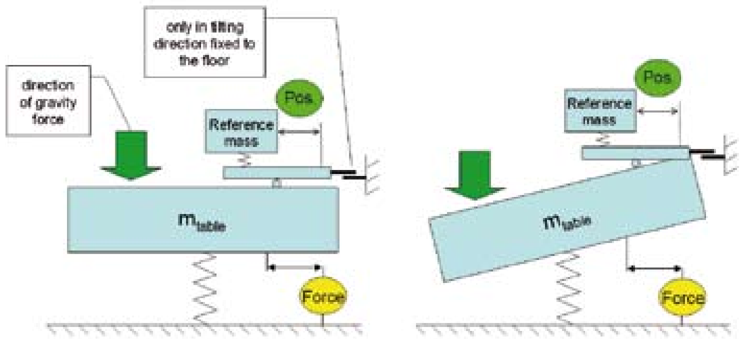

Figure 7. Hummingbird solution for tilt-to-horizontal-coupling.

By measuring position instead of velocity, the noise levels and resolution of the motion sensors at low frequencies are greatly improved. This lowers the start of the frequency range in which the controller is active to about 0.2 Hz, compared to 1 Hz for inertial control systems based upon velocity sensors. As a result, Hummingbird is the only vibration isolation system capable of a vibration reduction of -30 dB at 1 Hz, in six degrees of freedom (DoFs). Also, the low-frequency band where the system is sensitive to disturbance forces is minimised to a small band around 0.2 Hz, which greatly reduces the impact of the major disadvantage of inertial control systems (see above).

Figure 5 shows a one-dimensional representation of the basics of the Hummingbird concept. The technology can be used for isolation in three or six DoFs. The figure shows the passive vibration isolation, provided by soft springs supporting the table. These are air mounts or mechanical springs. The supports have a very low damping << 1%.

Solution for tilt-to-horizontal-coupling

In solutions that are based on inertial control, such as the Hummingbird technology, the problem of 'tilt-to-horizontal-coupling' occurs. If the table tilts, the gravity force acting on the reference mass will cause it to move (Figure 6). Theoretically, it is impossible for the sensor to distinguish this effect from acceleration. This means that the controller will misinterpret tilt as a horizontal motion, and will try to correct for it by accelerating the table in opposite direction. At low frequencies the tilting effect will become dominant over actual horizontal motion. Therefore, the tilting effect will limit the performance of the controller below the first eigenfrequency of the reference mass.

In order for reduction of vibrations to be effective at low frequencies, the tilt-to-horizontal-coupling problem needs to be solved. Figure 7 shows the patented solution used in Hummingbird. The sensor, including the reference mass, is fixed to the table in all directions except the tilting rotation. The sensor is attached to the floor with a fixation that is rigid only in the tilting direction and very compliant for the other five degrees of freedom.

Sensor behaviour at high frequencies

The motion sensor measures movement of the reference mass, which means that its sensitivity is directly linked to the movement amplitude of the reference mass. To enable sufficient movement of the reference mass at low frequencies, the eigenfrequency of the reference mass on its suspension needs to be as low as possible. However, the second and higher eigenfrequencies, the so-called spurious modes, will induce motion of the reference mass in unwanted directions. This movement is detected by the sensor and interferes with the feedback controller used for active isolation, causing instability of the controller. Normally, this limits the maximum controller bandwidth to about a quarter of the second eigenfrequency of the reference mass.

The mechanical design of the Hummingbird reference mass has been optimised to maximise second and higher modes. In practice, it is extremely difficult to realise a second mode more than 100 times higher than the first mode. For a reference mass with a first eigenfrequency at 2 Hz, the second mode can be elevated to about 160-200 Hz, which limits the controller bandwidth, and therefore the effective range of the active vibration isolator, to 40 Hz.

To enable higher controller bandwidths, and therefore lower compliance and transmissibility over a wider frequency range, the Hummingbird technology includes sensor fusion (patent pending). In this concept, a second sensor (for position, velocity or acceleration) is aligned with the position sensor. This second sensor corresponds with a reference mass at a much higher frequency. For low frequencies the controller uses information from the position-based motion sensor, for higher frequencies the information from the second sensor is used. This results in high resolution over a very large frequency range without problematic higher spurious modes.

Measurement results

Figure 8 shows the 6-DoF isolated Hummingbird platform presented on the Precision Fair in Veldhoven, the Netherlands, in December 2009, including the new technologies as described above. Measurement results show the transmissibility functions of the system (Figure 9) and the vibrations measured on the table (Figure 10). Note that these measurements were obtained with a separate set of sensors, not with the Hummingbird motion sensors used for the controller.

Figure 8. The Hummingbird platform.

The graphs in Figure 9 show the measured transmissibility functions of the platform (i.e. transfer functions from floor vibrations to table vibrations), in X-, Y- and Z-direction. Although the sensors used typically are not suitable to measure below 3 Hz, the measurements clearly show strong reduction of vibrations in the entire frequency range, in both vertical (Z) and horizontal (X, Y) directions. In vertical direction suppression of floor vibrations reaches a factor 100 in the frequency range around 3 Hz.

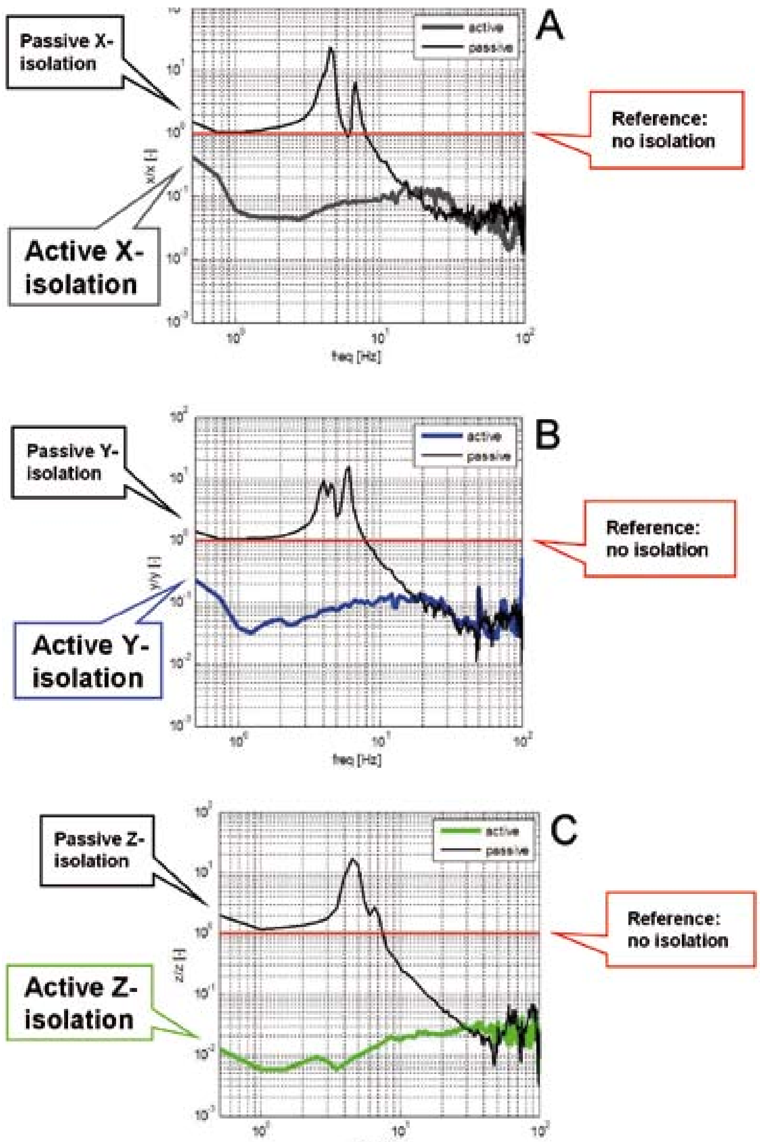

Figure 9. Transmissibility measured in X-, Y- and Z-direction.

The performance of the Hummingbird platform with respect to the NIST A1 vibration isolation standard was independently measured by VSL, the Dutch national metrology institute. Results presented in Figure 10 show that vibration amplitudes of the table, either caused by sensor noise or by transfer of floor vibrations, are well below the very strict NIST A1 specification. Note that below 5-10 Hz the accelerometers used for this measurement are not capable of measuring vibration amplitudes below the NIST A1 specification.

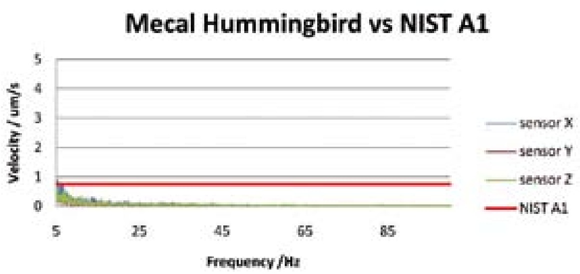

Figure 10. Hummingbird performance with respect to NIST A1.

Conclusion

In the Hummingbird vibration isolation concept three patented technologies were used to enable a considerable performance improvement compared to existing passive and active vibration isolation technologies. The position-based Hummingbird motion sensor enables active isolation starting as low as 0.2 Hz, with measurements showing -30 dB vibration suppression at 1 Hz in 6 DoFs. Overall, the test results show very low transmissibility of floor vibrations to the platform over a broad frequency range and very low vibration levels induced by sensor noise. The Hummingbird technology solves the problem of unwanted tilt of horizontal sensors at low frequencies and the effect of the spurious sensor modes at high frequencies, resulting in a very robust system in the entire frequency range.

The Hummingbird technology is offered by MECAL as a stand-alone supportive structure for a variety of sensitive equipment, or as a design-in for high-accuracy manufacturing and testing equipment.

Acknowledgement

The authors would like to thank the employees of TNO who contributed to the successful implementation of Hummingbird technology into a 6-DoF isolated platform.