MEASURING BRILLIANCE, THE TUITECH PROJECT (THE ULTIMATE IDENTIFIER)

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INTRODUCTION

When purchasing a diamond it's important to know that the gemstone has its own unique set of features and qualities; these aspects contribute to the value of a diamond. But how can a potential buyer establish the value of a diamond in a fair and accurate way, before buying the gemstone? Before the 20th century there was no standard process in which a diamond was graded, especially when it came to the quality and cut. Before the Gemmological Institute of America (GIA) created the 4Cs of Diamond Grading various other methods were used to record the colour of a diamond. For example, diamond graders used multiple A's to describe a colourless diamond whilst others used numbers, Roman numerals or even a brief description of the gem-quality such as blue white or fine white. Even though these multiple colour grading methods worked perfectly amongst local traders, the difficulty came when diamonds were traded internationally; in many cases diamond graders across the world used different types of grading systems. This reason alone would make it difficult to get an accurate valuation of a diamond before it was purchased. Fortunately, during the middle of the twentieth century the GIA developed an official diamond grading system called the 4C's Color, Clarity, Cut and Carat Weight these 4C's are now used globally to establish the value of each unique diamond.

Photonics is the science and technology of light. It encompasses generating, guiding, manipulating, amplifying and detecting light. It is an important core research carried out by Aberystwyth University's Department of Physics Photonics Lab for many years that eventually led to the development of the technology described in this paper. It could be aptly described as a serendipitous outcome of their research that resulted from a funded innovation 'open call' for potential applications for their recently published research into measuring the effects of passing light through translucent materials being seen by the R&D team at diamond Centre Wales (DCW). The DCW team had been for some time looking for improved and more technological methods of 'measuring' diamonds and interpreting the results in such a way that their typical retail customer could understand and relate to. Diamond Brilliance refers to how much white light is reflected within a diamond. The more white light reflected from within the diamond, the more brilliant it will appear to be. It can also be referred to as the quality of sparkle, light, and fire that makes diamonds shine. When comparing diamonds of similar carat weight and color, this Brilliance can determine the value of the diamond. It is noticeable that the most brilliant diamonds have the highest degree of clarity and fewest flaws. This means that every diamond gemstone is unique and requires individual grading on a subjective scale. Normally this is done by a skilled gemologist on behalf of an industry governing body in this paper you will be introduced to a novel and unique technological solution to accurately and repeatedly measure the Brilliance of a gemstone, particularly in a diamond. This technology can create a new standard of grading, incorporating new measurement scales and be able to evaluate additional features of diamonds such as Brilliance and fluorescence. Giving accurate, reliable, clearly defined grades to these factors to aid in correct valuations and certification. Adding an extra layer of value and a greater in-depth look into the diamonds make up and unique characteristics of that individual piece.

As you read on you may find this quite a long and involved paper but we felt it was important to set down the many and interlinking steps and new processes required during the TuiTech project to bring a totally new to the jewelry industry technology to completion. It necessarily ranges, initially, from some relevant university based research discovered in a literature search, through to some very complex research into material science , and the physics of light . Next we moved to actual laboratory based research and the creation of a 'proof of concept' which required access to software development and an understanding of user interfaces finally moving to a physical demonstrator to aid in commercialization which involved working closely with a design agency and a large company that specializes in complex engineering and technology challenges. All of which was part funded by various Welsh governmental business improvement grants and development schemes.

The technology uses two integrated spheres in contact with each other. The diamond, or other type of gemstone, is held at the intersection of the two spheres, supported on a mounting plate. The upper sphere incorporates a controllable light source and centrally mounted camera to image the diamond. Both upper and lower spheres are connected to a photo spectrometer to analyze the light that is present in each sphere. By this method the light intensity collected by the spectrometer in the upper sphere can be compared to the light intensity collected in the lower sphere. The ratio of the two can be correlated to directly provide a quantitative value for "Brilliance".

This correlation is valid because the further the cut of the diamond deviates from the optimal one to produce total internal reflection, more light is 'lost' into the lower sphere.

Excitingly this of course will require the creation of new industry standards that inform the buyer accurately about the "Brilliance" of the gemstone! (Later in the paper we will also learn of its ability to map and report on the "Integrity" of gemstones).

The equipment required is comparatively cheap to produce (i.e. a Raspberry PI microcomputer and LED light sources and spectrometers of varying cost) and all easily contained in a desk top friendly enclosure

What Is Diamond? (The Material Science Bit)

The word diamond comes from the Greek word Adamas, which means indestructible. It is the only gem known that is made of a single element - Carbon.

Diamond is a solid form of the element carbon with its atoms arranged in a 'metastable diamond cubic (isometric) crystal structure'. Diamond has the highest hardness and thermal conductivity of any known natural material, properties that are used in many industrial applications.

Because the arrangement of the atoms in diamond is extremely rigid, very few types of impurity can contaminate it (two exceptions of which can be boron and nitrogen). Small amounts of impurities (about one per million of lattice atoms color diamonds blue (boron) yellow (nitrogen) brown (defects) green (exposure to radiation). Other colors can include purple, pink, orange or red. Diamond also has a very high refractive index and an equally high optical dispersion ratio.

Most natural diamonds are considered to have ages of between 1 and 3.5 billion years. Most were formed at depths of between 150 and 250 kilometers (93 to 155 miles) in the earth's mantle although a few have come from as deep as 300 kilometers (500 miles). Under the high pressures and temperatures found in the earth's mantle carbon containing fluids dissolved various minerals and replaced them with diamond. Much more recently (only a mere hundreds to tens of millions of years ago) they were carried to the earth's surface in volcanic eruptions and deposited in igneous rocks known as kimberlites, or kimberlite pipes, and lamproites , The complex volcanic magmas that solidify into kimberlite and lamproites are not the source of diamonds and should be considered as the elevators that bring them, and other minerals, to the earth's surface. Although rising from much greater depths than other magmas, these pipes and volcanic cones are relatively small and quite rare.

Today diamonds are mined in about 25 countries on every continent except Europe and Antarctica. Until the 20th century very few diamond deposits were known. For 1000 years starting in roughly the 4th century BC, India was the only source of diamonds. In 1725 important sources of diamonds were discovered in Brazil and in the 1870's major finds in South Africa marked a major increase in the supply of diamonds. Major diamond producers now includes several African countries, Siberia/Russia, Canada and Australia.

An octahedron is considered to be the most common shape for a (rough) diamond crystal (Figure 1) though cubes, dodecahedra and combinations of these three shapes are also quite common. All are highly symmetrical, with equal dimensions in three perpendicular directions, and all can be considered to be manifestations of the cubic crystal system to which the mineral diamond belongs.

Figure 1: A Diamond In The Rough

Some exceptions include the flat form called a macie, which is a twin or composite crystal, as if mirrored across its central line of symmetry, etched crystals, with rounded surfaces and, sometimes elongated shapes. Triangles sometimes result from subtle changes in height on a diamond's octahedron face and are known as trigons.

Diamond shape (Figure 2) refers to the geometric appearance of a diamond. Diamond shapes are categorised into two groups: round diamonds and fancy shape diamonds. Round brilliant diamonds are the most traditional diamond shape.

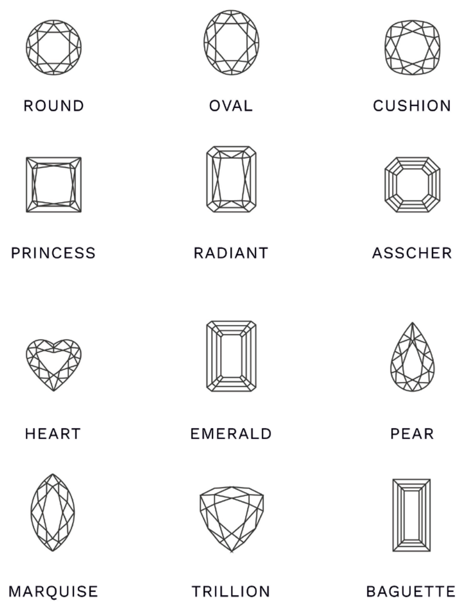


Figure 2: Cut Diamond Shapes

Diamond is also renowned for its hardness. Hardness is the measure of a substances resistance to being scratched, and only a diamond can scratch another diamond. Diamond is considered to be one of the hardest substances known to man. The Mohs scale is a hardness scale developed in 1822 by the Austrian Friedreich Mohs as a criteria for mineral identification. It can help with appreciation of the hardness of diamond, the scale ranks 10 minerals; harder minerals, with a higher number can scratch those with a lower number. The Mohs scale (Figure 3) is considered to be relatively stable until it reaches the eighth mineral Topaz, but it then jumps exponentially from Corundum (colorless Sapphire) to diamond. Because diamond must be used to measure its own hardness it is in fact very difficult to measure. A diamond is 58 times harder than the next hardest mineral Corundum, from which Rubies and

Sapphires are formed. Despite its reputation as the hardest natural substance on earth if Diamond is placed in a furnace at 1405 degrees Fahrenheit (763 degrees Celsius) it will 'vanish' and only a very small amount of carbon dioxide will have been released, yet diamond is brittle and if hit hard enough with a hammer it will shatter!

Figure 3: The Mohs Scale

Unusually for a mineral diamond repels water, due to its strong bonding and carbon composition, but attracts wax and grease. These two properties provide an effective means of separating diamond from other minerals during mining operations. Washed gravel containing diamond is flushed with water over a sloping surface covered with a mixture of wax and grease (a grease table). The diamond sticks to the table, whilst the wetted waste minerals wash over it. Gem diamonds readily pick up a greasy film but cleaning with ammonia or a good detergent easily restores their brilliance. Diamond has a specific gravity of 3.52 which means that a diamond is 3.52 times denser than water. What makes diamond (simple carbon) so dense? The answer is heat and enormous pressure. As discussed here earlier far below the surface of the earth pure carbon was compressed under intense heat and pressure which caused it to crystallize and form diamond. The heat was probably around 1400 degrees Centigrade but the pressure was immense probably

greater than 300 tons per square inch.
(Specific gravity deals with the volume of a substance based on its density. i.e. one pound of lead is much smaller than one pound of water. Specific gravity is the comparison of a certain volume of water to the same volume of another material)

The Optical Properties Of Diamond (The Physics Of Light Bit)
One of the unique optical properties of diamond is its ability to split light rays on their way through the diamond. Light rays do not pass through the diamond, but are instead broken and reflected back at different angles. This optical property of breaking light rays and reflecting them back creates diamond's unique sparkle. Some of the rays that penetrate diamond are broken and are reflected back through the facets of the crown. This reflection creates a sparkle – the diamond's "fire". Due to the different angles in which some of the light is reflected back, the light reflected back from the diamond is white. The rays reflected through the diamond's table as white light are described as its "Brilliance."

The TuiTech project is all about creating a stable and repeatable technological method for measuring this "Brilliance" which is currently measured subjectively by a highly skilled gemologist.
The rays of light that reflect back through the facets of the crown of a cut and polished diamond are partially broken, like the rays of light passing through a prism. A ray of light consists of a spectrum of colors, which includes red, orange, yellow, green, blue, indigo, and violet. This spectrum is often seen in a rainbow and can be observed when light is refracted or dispersed through various mediums. This phenomenon is known as dispersion, and it occurs because different colors of light bend by different amounts when passing through a medium, in this case we are only focused on diamond. These colors flash through the polished facets, and the play of colors at different angles create the diamond's fiery look and brilliance. Another optical property of diamond is its mirror-like effect. Unlike glass, which allows the light to penetrate it and "move on", diamond's break up the light rays that penetrate through them. This quality creates a mirror-like effect, light bouncing back to the viewer, which keeps them from looking "through" the diamond.

The Speed Of Light
A commonly quoted science 'fact' tells us that the speed of light is a constant 186,000 miles per second to which you also have to add the words, "in a vacuum." When light travels through matter - air, water, glass, or diamond, for example - it travels slower than 186,000 miles per second. The actual explanation for this is to do with the way light interacts with the electrons present in every

atom and is far too complex to be required for inclusion here, but you can visualize this slow-down by thinking of light rays having to make little detours every time an electron gets in the way.
Most clear and colorless objects retard the speed of light only a modest amount. The air we breathe has a billion-trillion atoms per cubic inch. Spaces between atoms are much greater than the size of the atoms themselves, so air reduces the speed of light by just a few hundred miles per second - not enough to notice under most circumstances. In water and ice, which have thousands of times more atoms per cubic inch than air, light travels about 140,000 miles per second - 30 percent slower than in a vacuum. Window glass drops light speed to 120,000 miles per second, similar to the travel time through most common minerals, whereas lead-containing decorative glass, the kind used in chandeliers and cut glass, slows light even more, to about 100,000 miles per second (lead has lots of electrons that get in the way). Diamond slows down light like no other known colorless substance. Diamond is crammed with electrons – nothing has atoms more densely packed than diamond so light travels through diamond at less than 80,000 miles per second. That's more than 100,000 miles per second slower than in air.

Light does not always bend when passing between different materials. If light rays strike a clear substance head on or at a modest angle - like the path of light coming through your window - most of the rays will travel straight through without bending.

Diamond plays the reflecting light trick better than any other colorless substance. Light enters a faceted gemstone from all sides, but it may bounce back and forth several times inside before it finds a clean, straight way out. All this changing direction accomplishes something very dramatic, because so-called white light actually contains all of the rainbow's colors. Each color - red, orange, yellow, green, blue, indigo and violet - bends and reflects inside the diamond slightly differently. The farther the light travels, the more the colors separate, or "disperse." Bounce light inside a diamond just two or three times and the colors disperse spectacularly. (Diamond-like substitutes, including "cubic zirconia," a crystalline compound synthesized from the elements zirconium and oxygen, attempt to mimic this light-dispersing property, though they fall short of diamond's brilliance and unrivalled hardness.)

If you look closely at a cut, polished and faceted diamond, you can see that it soaks up white light and breaks it apart like a prism, dispersing it into a rainbow of colors. Diamonds sparkle and dance with colored light; each of its dozens of facets produces its own dazzling display. Other natural gemstones disperse white light to some degree, but none comes close to diamond's ability to reveal the colors of the rainbow.

Cut

The cut, or faceting, of a diamond has the biggest impact on its perceived beauty but sometimes the least difference in its price compared to its color, clarity and carat weight. The word cut has several meanings when it comes to diamonds, the cut of a diamond does not just mean its shape (Round, Brilliant, Princess, Oval, Cushion, Baguette, etc.) but also addresses the symmetry, polishing, angles and proportions of each physical aspect of the diamond in question. The quality of the cut determines the diamond's sparkle and brilliance. A well-cut diamond will refract the light that enters the diamond and return most of it (the light) through the top table to produce the desired sparkle and brilliance. The angles and proportions have to be exactly right to optimise the reflection of light back to the viewer's eye.

What Happens To Light In A Diamond?

"A diamond's beauty is all about how it handles light. The most stunning diamonds reflect, refract and disperse light in a glorious display of fire, brilliance and scintillation."
Firstly we need to remind ourselves about the anatomy of a diamond (Figure 4)

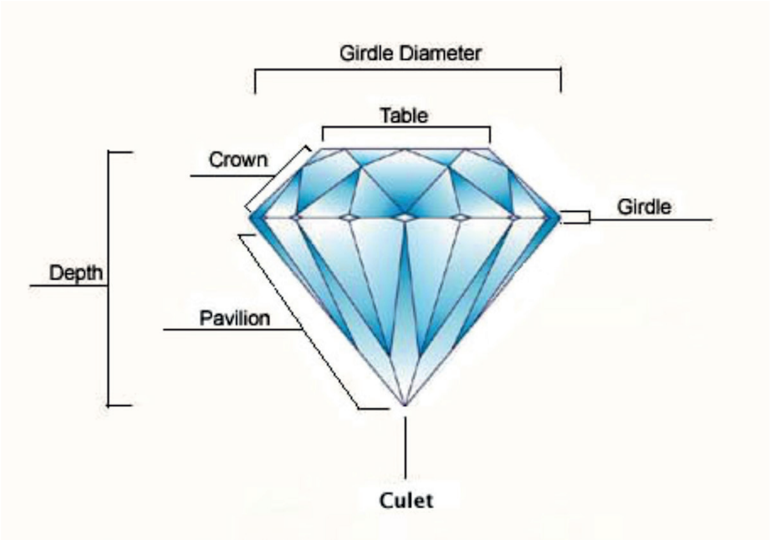


Figure 4: The Anatomy Of A Diamond

Diamond cutters attempt to get the best light performance out of a stone by precisely controlling its proportions and expertly angling facets to direct light in specific ways. When light hits the surface of a diamond some of it is immediately reflected by the crown facets and some enter the stone. The term given to these reflected flashes of white light is "Brilliance". A well-cut diamond has more "Brilliance" because the angles of the stone reflect light back to the viewer, instead of allowing it to leak out of the base or sides. The light that enters the stone is refracted by the diamond's internal angles and is ideally directed back out through the table. As the refracted light exits the diamond, it's dispersed into a spectrum of colored light. Diamond dealers refer to these rainbow colours, caused by light dispersal, as "Fire". (Figure 5) It is well documented that older cut diamonds with steeper crown angles and small tables have more "Fire", but usually, this is at the expense of "Brilliance". A well-cut diamond will have a good balance of "Brilliance" and "Fire". "Scintillation" is the name given to the intense dancing sparkles created when a diamond moves. Ideally, this effect is visible across the entire surface of the diamond with no, or very few, dull patches.

Figure 5: How Cut Affects A Diamond's Light Performance

The Way A Diamond Handles Light

Different diamond cutters will naturally have different levels of skill, experience and expertise and so cut their diamonds slightly or even significantly differently. Each rough diamond crystal will have its own distinct inclusions, such as Nitrogen gas pockets, occurring at random locations within the crystal matrix. The diamond cutters are trying to cut the biggest and heaviest diamond they can from the rough crystal. Cutting diamond to the best possible cut typically means losing some diamond carat weight during the cutting, there will therefore always be a compromise between perfection and size.

The typical Brilliant cut diamond is cut with 58 facets, 33 on the crown and 25 on the pavilion. On a well-proportioned diamond these facets will be uniform and symmetrical; if they are not, the diamonds ability to refract and reflect light will be marred.

How Light Affects A Diamond's Appearance
There is often a noticeable change in how a diamond appears in sunlight, in candlelight and under artificial lighting. This change is yet another reason for our pursuit of the TuiTech project. Whenever a diamond moves or is moved, for example when on the finger, there should be an almost mesmerising display of glinting lights and colours as light reflects on the facets and the facets reflect the light on each other. This symphony of reflected light is composed of "Brilliance" (the sum total of light reflected from the diamond, "Fire" (the dispersion of light into the colours of the spectrum), and "Scintillation" (the pattern of light and dark areas and flashes of light or sparkle when a diamond is in motion.

Brilliance
The perception of a diamonds 'brightness' is referred to as it's "Brilliance". Generally speaking "Brilliance" is not simply the direct reflection of light from the diamond's surface facets back into the eye of the observer, "Brilliance" is far more complex than that. The amount of "Scintillation", the availability and types of light sources and their contrasts are all aspects of "Brilliance", yet these aspects are not the only ones. The ever changing factors that come with an imperfect human perception fall into this characterisation. It can be argued, and indeed it is by the developers of the TuiTech technology, that a diamonds "Brilliance" is the essential factor in determining its overall attractiveness (and therefore it's perceived 'value' to any potential purchaser). This is because when a diamonds "Brilliance" becomes diminished by any and all of the many factors previously discussed its "Fire" and "Scintillation" are also reduced to a greater or lesser degree.

Ultimately the quality of a diamonds "Brilliance" is determined by the quality of its cut, a well-cut diamond is always going to be a "Brilliant" diamond!

Diamond Centre Wales And The TuiTech Project
Since its inception in 1978, Diamond Centre Wales (DCW) has earned a reputation for the design and manufacture of diamond jewellery. Their craft reputation and business has grown hand-in-hand over that time. With an annual turnover of £2million DCW now have over 15,000 customers on their database. They have also extended the business to incorporate their interactive diamond lounge, conference facility and shop. From their purpose built, merchant quarters in Talbot Green, near Cardiff, South Wales, they provide a complete "concept to creation" service, all undertaken

in-house. Their 21 employees include expert teams consisting of software developers, artists, designers, diamond graders and Goldsmiths, who create over 1000 bespoke jewelry pieces each year. These teams are supported with a state-of-the-art digital design and prototyping suite and an R&D department. DCW has a fully equipped Workshop with facilities for up to 16 Goldsmiths, and a teaching facility for training in traditional and modern Goldsmithing techniques.

As previously indicated all diamond stone grading is currently done by certificated grading houses with large labs and trained staff, each stone grader is different and can grade the same stone differently. This creates issues where as two identical stones can be purchased and they will be graded exactly the same on the certificate, however, one will technically look ‘better’ than the other. The TuiTech technology is designed to electronically grade those stones and give qualitive and quantitive data, without bias, and on a measurable and uniformly repeatable scale. TuiTech was developed as an innovative, apparatus and unique method for the assessment of gemstones. More specifically for objectively determining the “Brilliance” and fluorescence of a precious stone along with cut, colour and where that stone was mined to ensure ethical mining practices are adhered to along with potential disruption in the trading of illegally mined/sourced diamonds.
(There is equipment currently available that can only detect lab grown from natural diamonds and this equipment can no longer be considered to be a new technology).

Once the research phase of the project began we discovered another unique property of the technology, namely its ability to identify and quantify the “internal integrity” of the diamond being examined. By “integrity” we are attempting to describe the TuiTech technologies ability to see into the diamond and measure the inclusions within. Inclusions and blemishes are the structural imperfections which affect the clarity grading of the diamond. These inclusions are often crystals of diamond or a foreign material that has formed within the stone affecting its internal composition. The variety of possible inclusions is actually quite large ranging from small (very small) diamonds, other gem crystals such as Sapphire and Garnet as well as other minerals and elements such as Boron, and even minute Nitrogen gas pockets can be trapped within the matrix of the diamond. The ability to recognise, quantify and register these inclusions means that each diamond being examined by the TuiTech technology can be identified and recorded as having its own unique ‘finger print’. This ability to spot and record the “integrity” of the diamond once again, like its abilities with “Brilliance", requires the creation of a whole new lexicon for describing the nature and integrity/quality of a diamond.

The Development Of TuiTech

We now need to take a more detailed look at the R&D work that went into the development of the TuiTech project.

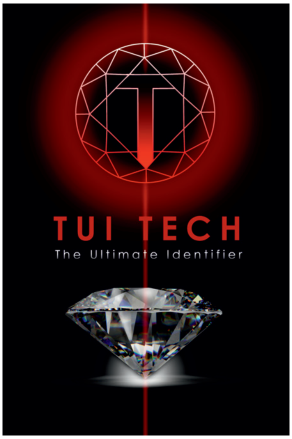


Figure 6: The TuiTech Project Logo

The basic theory behind TuiTech uses two integrated spheres in close physical contact with each other. The diamond is to be held at the intersection of the two spheres, supported on a mounting plate. The upper sphere incorporates a controllable light source and centrally mounted camera to image the diamond. Both upper and lower spheres are each connected to a photo spectrometer to analyze the light that is present in each sphere. By this method the light intensity collected by the spectrometer in the upper sphere can be compared to the light intensity collected in the lower sphere (Figure 7). The ratio of the two can be correlated to directly provide a quantitative value for brilliance. This correlation is valid because the further the cut for the diamond deviates from the optimal one to produce total internal reflection, more light is 'lost' into the lower sphere. Camera imaging of the sample can be used to quantify symmetry and sparkle while spectrometer values can also support the camera image analysis for fire. Additional features such as levels of photoluminescence which can provide further unique characterization of samples can easily be incorporated into this design.

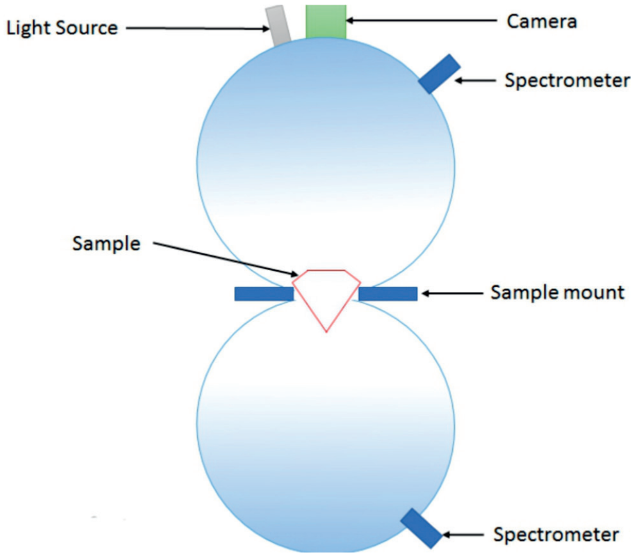


Figure 7: The Two Spheres

The arrangement of the spheres will eventually be optimized to accommodate a wide range of sample mounts for a full range of sample sizes and gemstone shapes.

The use of these integrated spheres is important in that it ensures accurate measurement of the light intensity irrespective of the initial direction of the incident rays, this is an important feature when dealing with a highly faceted sample of a cut diamond. The use of two complete spheres also ensures the scientific and optical validity of the principal of operation and conforms to the supporting literature associated within the field. However, the use of two spheres arranged in this way and in this specific application can be considered unique and is heavily patented.

Previous work in this field by our university partner (Led by Dr Simon Astley and Dr John Tomes from The Centre For Photonics Expertise in the Department of Physics at Aberystwyth University) had shown that creating low cost, research quality, integrating spheres could be made using a simple and basic Fused Deposition Modeling (FDM) 3D printer. Specialist internal coatings were also developed to produce high quality research outputs. What makes this particular configuration ideal for use in our particular application is the high efficiency of internal reflection inside the spheres, any point within the sphere can be used to determine the average of both the total light intensity, and color, of the entire sphere (Figure 8).

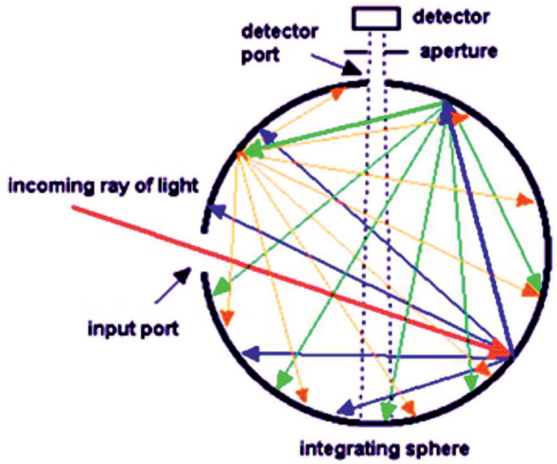


Figure 8: Light Performance Within A Sphere

We also developed a novel highly effective internal coating based on a Barium Sulphate substrate which was found to give us an incredibly high level of efficiency in capturing the light rays which allowed for the following developments

a) In the upper sphere, we were able measure the total light that is emitted from the table and crown of the diamond, both of which are the desirable locations for best level of Brilliance, as well as an average "color" and ratios of those colors if high specification spectrometers were used.
(A spectrometer measures the reflection or transmission of light by an object, usually in wavelength ranges from about 360 nanometers (nm) to 760 nm.)
If we have a consistent calibrated set of light sources (IE: white light source, blue, red and green LEDs, etc.) then we can determine the loss of light across the entire spectrum for each individual diamond, with perfect reproducibility. As the way that a diamond will reflect the light will be uniquely individual to itself, this means we now have a very effective, low-cost method for collecting and measuring the light emitted from the diamond.

b) The above is also true for the lower sphere, we were able to work out and calculate how much light escapes through the bottom of the diamond by working out the ratio of light between the upper and lower spheres, and we can therefore now give a numerical value to the "Brilliance" of the diamond. If we measure the total light in both, the higher the percentage of light in the upper sphere compared to the lower, would indicate the diamond has a much higher "Brilliance", as it is releasing more light in the viewed parts of the diamond from the users perspective. As we would have two spectrometers, one in each sphere, we could even determine the brilliance of the diamonds with respect to individual colors, IE a "fire" diamond could be shown to be more brilliant in red then other colors.

c) It allows for the finer measurement of precise color in the diamond using a camera mounted near the top to look at how the color bounces around in the diamond itself, where even options such as lasers on small DC motors and an O drive to move the laser in small increments, to work out where things such as impurities etc. may lay via measuring differences in the light measured output in the upper and lower spheres.

The spheres must have a minimum 90% reflective coating for them to be effective, as the ports are generally very small in comparison to their volume. For context, if you have sphere which is approximate 25cm diameter, if you assume the average port size will a roughly a 0.8cm entry inside the sphere, it would allow up to 10 ports to be active on each sphere and still maintain the high efficiency and repeatability which could allow for future upgrades, or new ideas to be incorporated into the technology.
The (Figure 9) below shows the schematic used as an initial proposal for the final design of TuiTech based on the universities testing and research.

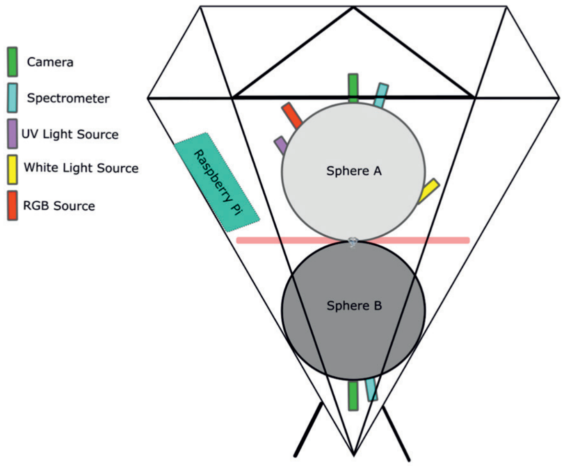


Figure 9: Initial Schematic

The diamond ‘shell’ was initially visualized as an outer casing which can be modified, depending on whether size upgrades or a different appearance is desired. (We will look at this aspect of appearance later in the paper) The two spheres were 3D printed in 2 sections each, the lower and upper half which would then slot together via a bracket (Figure 10) such that the insides of the sphere can be accessed for the polishing of the rough layer printed surfaces and the Barium Sulphate coating could be applied.

Figure 10: Two 3D Printed Sphere Halves

Ports were then either manually drilled or the spheres could be printed with the holes for the camera, light and spectrometer fittings in situ. For the encasing, it was printed as 4 sections, a screw bottom base which goes just below the lower sphere to install and remove the camera and spectrometer, two middle sections which allow for the insertion of the diamond mount (Figure 11) and installation of the Raspberry Pi, and those also having supports to hold the upper sphere in place. And then a top section which includes the crown and table which lifts off, for easy access to the cameras, spectrometers and light sources for the upper sphere, such that future maintenance is easy.

Figure 11: Two Half Spheres Assembled

One of the more important research tasks for developing the technology was investigating and specifying the microcomputer to be used. The exact model to be used is dependent upon any number of variable circumstances, such as the preferred coding language of the engineers/technical support in charge of writing the code for detection and then transmission of that information to the server, size/fit necessities or computational power requirements. The largest device recommended is roughly the size of a credit card and 1 inch thick (a Raspberry PI) whereas the smallest, an ESP- 32 is a 6x6x5mm system, but with lower computing power. The amount you process the information in the initial stage (Whether you try to determine what is in-situ, or whether you have effectively a system which just detects that there is something there, and then relays that information to a larger server to process) will determine the processing power and therefore the required micro-computer. It can be designed such that the internal computer feeds information back to an external desktop PC, so that it's the PC that then drives all the calculations which feed back to the user. As most of these small computers have Wi-Fi/Bluetooth compatibility, there can also be options for remote use of the technology. (Figure 12) shows an ESP32 board, rigged up to a camera, a UV Source and a simple spectrometer, which is controlled via a Bluetooth controller from a laptop.

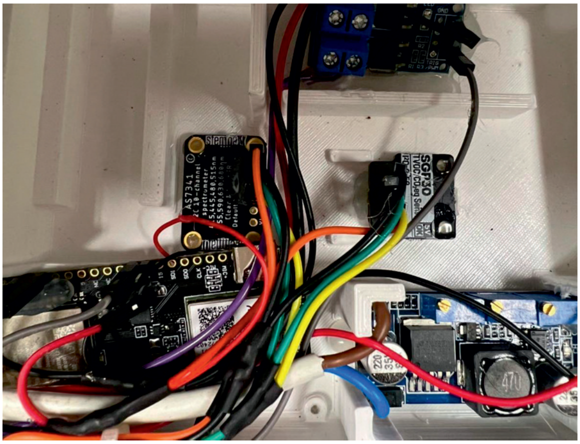


Figure 12: The Circuitry Test Rig

Light Sources

For a white light source, there were various options from very expensive finely tuned flood sources (£500-£1000/$650-$1300) or alternatively a small filament bulb (£5/$6.50), what was important to this project were two crucial aspects; the broadness of the light sources spectrum (no point in having a light source which is low in one part of the light spectrum) and also whichever source we selected having comparable and repeatable emission if we were to purchase them in volume. Though this wasn't critical as we planned for every machine to be calibrated to its own sources and calculate the brilliance etc. via the loss; but they should ideally all be somewhat similar.

UV-LED

LED'S were considered rather than lasers for the planned luminescence measurements. They are less expensive and generally the most readily available, this allowed for the use of a high-power LED which then allowed for maximum fluorescence potential. They are the most versatile UV light source in terms of the lifetime (20000 hours typical use time) but also have much less associated risk then say a laser which produces an immense amount of heat, and therefore accommodating for that heat within the technology would have been problematic as well as more expensive. The use of the LED also allowed for less needed precision in the setup, as they are "flood" light sources, you don't have to worry about fine tuning the source's output location during manufacturing or the source moving drastically effecting the results. This then allows for a quicker manufacturing time when scaling up production, alongside resulting in a much more reliable and robust system for use in a workshop or office environment. The SC2111 and AAP 9654 LED's shown below (Figure 13) are the ones we used to conduct the trial luminescence measurements, with the 275nm source performing much better as it's a higher energy photons were also able to induce luminescence.

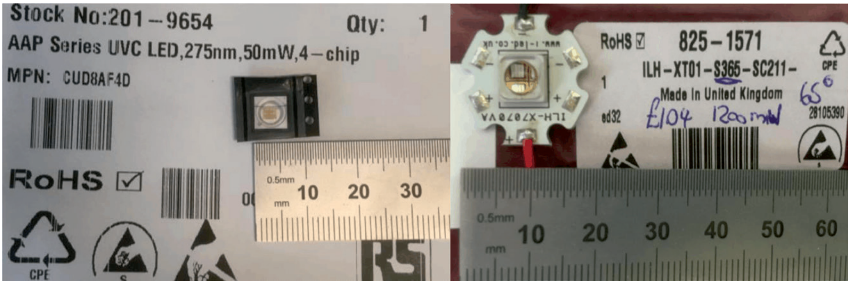


Figure 13: LED's

Camera

Once again, the exact camera to be used in the technology can be upgraded dependent on the end users desire for higher resolution imagery, but a relatively low cost camera setup such as the Pi-Camera could be used which is quite low cost yet adequate for the desired results. During testing we found that the Pi camera performs perfectly fine, but potentially just simple sensor upgrades such as the 8MP Sony IMX219sensor produced high quality images with good resolution (a 4K image) for a small increase in cost on the base price of a Pi Camera. Higher resolutions of camera and sensors could be used but anything above a certain cost inevitably will give diminishing returns. The (Figure 14) below is a 16mp Arducam, which we tested during the research project, and which allowed for the more than adequate imaging of the diamonds inside the integrating sphere.

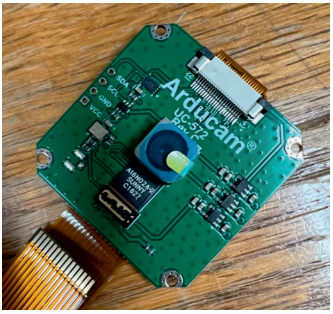


Figure 14: 16mp Arducam

Spectrometers.
The base cost of commercializing the TuiTech project was always going to be defined effectively by the quality of the spectrometers used, although we could have used lower cost options for the UV source, computing unit, camera and even visible light sources, the spectrometers are the most critical parts of the technology. During our research we used majority flame spectrometers , which have an approximate cost of £3500 ($4500) each.

These however produce incredibly accurate color and intensity measurements which are the essential function needed for TuiTech to have the accuracy and repeatability desired to break into the diamond market. There are cheaper alternatives that have and can be used (£2000/$2500 each) however having used flame spectrometers   in other research projects our university partners assured us that they are a very high-quality and necessary item. The spectrometer needs a range from 300-800nm that is essential for a high spectral resolution (<2nm) is required so we can accurately determine not only the total light in each sphere for "Brilliance", but also the color of light in each sphere to accurately quantify the luminescence and discover the inclusions and color of the diamond.

Interface
The integration of a screen (Figure 15) into an outer-casing was tested, in order to show real-time displays of the data being obtained and the images of the diamond without the need for an external display, this did work however organizing the internal wiring to the Raspberry PI whilst it is mounted to effectively the table of the outer casing during the research phase proved to be rather

tricky but eventually feasible.

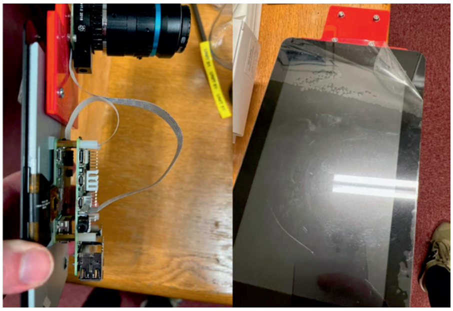


Figure 15: The Test Rig Interface

Mounting/Holding Of The Stones

Mounting of the diamond correctly is essential for the measurements to be made, ensuring tight fittings secure the diamond to reduce loss of light between the top and bottom around the diamond, whilst also not damaging the diamond, was difficult due to the huge range of sizes, and types of diamond cuts that are commercially available. We adapted our approach and looked at several different mounting technologies from crude wire set ups to advanced smart gel solutions, once we had tried and tested each approach a solution was agreed that best fit the applications needs and ease of use for the user and through the use of additive manufacturing techniques we were able to create a collection of bespoke holders.

A range of different types of polymer coatings, uniquely cut mounting solutions and research into the literature about light absorbing coatings were researched and tested. Mounting the diamonds with unique holders is possible and does work, but would require a holder for each cut of diamond as well as a specific carat size (IE: 0.64-0.66ct, 0.67-0.69ct, 0.70-0.2ct etc.) which is realistically unfeasible due to the sheer number of holders that would need to be produced. Polymer coatings have had good success resulting in being able to use smaller ranges of holders (IE: 0.60-0.75etc) which whilst an improvement, still isn't perfect and gets degraded over time. Currently we are testing thin film oxidized metal coatings, which should allow ranges of 0.25ct steps, whilst also ensuring zero light leakage between the measurement sections.

The unique design of the TuiTech technology requires a complete isolation of the light emitted from the top of the diamond from the bottom. As this will be the first technology to be able to do this, no solution for the mounting of gemstones in general in this manor has ever been undertaken, so there isn't any prior research available into mounting various cuts of differing sizes using either a single, or small number of holders for us to follow. Although diamonds are considered to be strong, hard, materials, they are not particularly stable and can easily crack if we were to apply sufficient pressure to the wrong spot, the splitting or cracking of a diamond is a possibility if mounted too tightly using the incorrect method to exclusively isolate light ingress. The actual design, structure and coating of the holders is currently awaiting approval and patenting so no image can be shared here at this time.

Full Commercialization

The final step of this phase of the TuiTech project was to move the ideas and proof of concept research into a fully commercialized package. A physical demonstrator of the product enclosure and internal technology needed to be produced along with the development of the initial design layout of a user interface for TuiTech would also be required. This involved working closely with a product design consultancy, Iterate UK , who steered and assisted us through the following steps.

The project brief for the scanner encasement was; "To create at least 3 detailed design concepts of an enclosure for the Tui-Tech technology system. The inspiration for these concepts is to be informed by existing devices which have design parallels with the device."

Amongst the various options being considered the following guidance points were used and this is a good indication of the level of detail we were working towards.
Color, Shape, Finish, Size, Materials, Manufacturing Methods (including for spheres), Diamond Holding and Insertion, Power, Maintenance and Data Display. Display Position, User Controls, Status Indicator and Operation, Stability, Handles, Expansion, Cooling, Connectivity.

We mocked up a typical scenario (Figure 16) in which this product would be used. The product is placed on a desk with a person sat at a chair at the desk. The person's eyeline is 250mm above the position of the display, and the screen is 300mm in-front of the person.

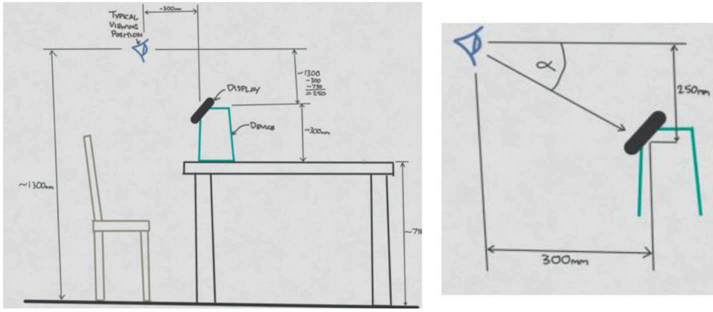


Figure 16: Viewing Height And Angle Mock Up

Next we considered competitor products although there are no products on the market that will deliver the depth of data the Tui-Tech technology is intended to provide. Although there are multiple products available for the testing of diamonds, these products typically determine if the gemstone is made as nature intended, a natural diamond, or manufactured in some way, but they do not provide any further detail of the quality of the diamond being assessed. (Figure 17)

Figure 17: Similar Competitor Products

We then created a series of moodboard's (Figure 18) to explore various existing concepts of a similar nature from which to draw inspiration.

Figure 18: Various Moodboard's

A Color, Material & Finish (CMF) analysis identified how the product would look and feel to the user and some of those options are shown in Figure 19.

What is CMF?
In the context of design and product development, Colour, Material, and Finish refers to the strategic selection and coordination of these three elements to create a functional, sustainable and aesthetically pleasing product.

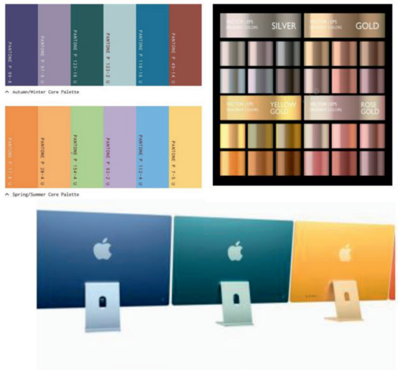
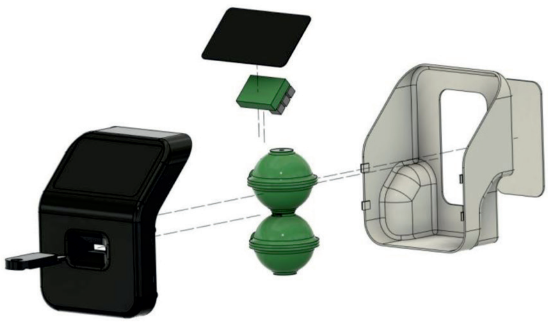


Figure 19: CMF Analysis

In the next step we considered some conceptual designs.

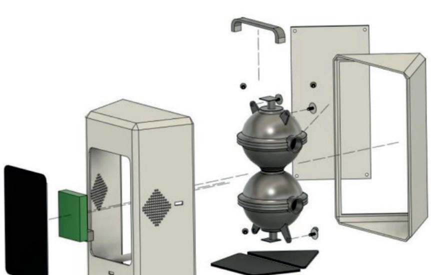
Concept number one
A box shaped device split into two halves. The display is inclined at 45° to allow easy viewing for a user sat at a desk or workbench. Scallops on the rear side provide a groove to easily pick up and move the device. A rear push fit maintenance hatch allows access to the internals of the device for repairs. A single USB port is located on the side to allow extraction of data. The gemstone is to be inserted into a slot on the front side of the device. (Figure 20)



Pros	Cons
Two halves can be easily manufactured by injection moulding	Design is only suitable for injection moulded plastics. Alternative materials will be difficult
Device is relatively compact	Pocket is required to insert gemstone carrier
Display is oriented at 45°	

Figure 20: First Conceptual Design

Concept Number Two
The display is oriented vertically. This allows the device to be quite tall and thin. An external handle allows for easy moving and transportation. A rubberized base stops the device moving on the work surface. A rear maintenance hatch is released with 4 screws to give access to the internal enclosure. The spheres are mounted to the enclosure with fir tree clips for quick and simple assembly. (Figure 21)



Pros	Cons
All components are assembled into one half of the enclosure. Easy assembly	Design is quite simple
Design is suitable for an injection moulded plastic part, or also an aluminium or steel fabricated assembly	Bosses required for the maintenance hatch fixings to screw into. Could be difficult to manufacture
Fir tree clips to secure the sphere assembly is very simple and quick to install.	

Figure 21: The Second Conceptual Design

Concept Number Three

The rear enclosure follows the form of the sphere assembly. This allows the gemstone carrier to be inserted much closer to the spheres. The carrier does not need to be as long. The display is installed at a 45° for optimum viewing angle. A number of buttons are built into the front surface with backlit LED's to create an accent color. The sphere assembly is installed in the enclosure by gluing tabs together. The rear enclosure is hinged with a magnetic clasp to keep the enclosure secure during use. (Figure 22)

Pros	Cons
Gemstone carrier is very small	Contoured design does not look very aesthetically pleasing
Opening the maintenance hatch is very simple	3 pieces of enclosure
Design is very compact	Unclear if magnet would interfere with spectrometer or other electrical equipment
	Glueing the spheres to enclosure is permanent
	Inserting gemstone is on the rear of the device

Figure 22: The Third Conceptual Design

The User Interface (UI) Development

The development of an initial design layout for a user interface for the TuiTech machine had the goal of developing a prototype user interface that would enable us to fully demonstrate the product function to potential customers, manufacurers and investors. It was determined that it would be helpful if the final prototype UI could run on mobile devices/desktop devices. The prototype UI will eventually be placed into the prototype machine but for early testing it was decided it would be easier to evaluate the UI on mobile devices. This work culminated in a wireframe design of the UI being created as well as other visual concepts for the aesthetic design of the interface. Our recommendations were that the wireframe demo be interrogated to ensure that all the functionality requested were present and to inform if any changes need to be made. We implemented the chosen aesthetic style onto the basic wireframe screens to build-out the prototype UI. This was be done using Adobe XD software which allowed for the prototype user interfaces to be run on mobile devices. At the end of the work package we had a prototype UI, accessible via a weblink, which could be shared to multiple people and devices to run and test the user interface. (Figure 23)

Figure 23: The Interface Screen

For the UI to function as intended, 30 screens needed to be designed and built. A number of these are variations of the same screen showing selected items, data input or segments of a loading icon spinning, etc. These 30 screens were created in Adobe XD and a few of which are shown below in Figure 24.

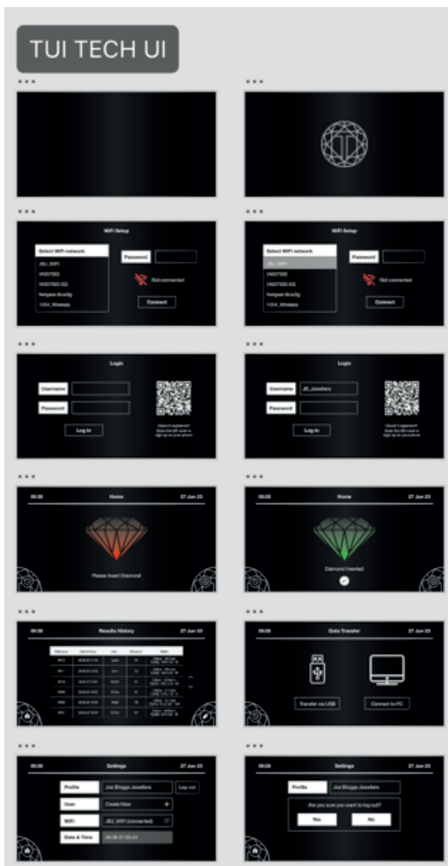


Figure 24: Various UI Screens

There were also nine main master screens of the UI which were required to be created in multiple variations, some these are shown in Figure 25.

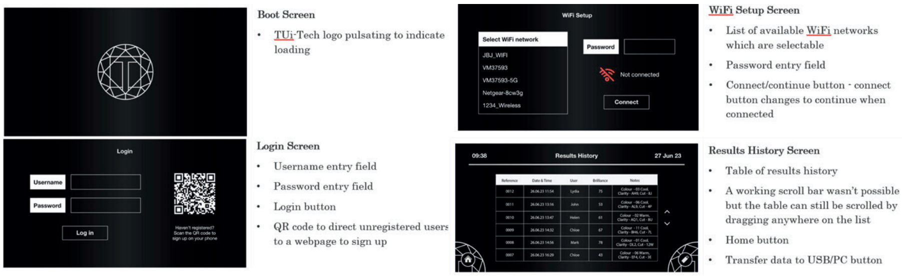


Figure 25: Master Screens

These pages then needed to be linked together to define the interactions and animations/transitions.

The Final Step – Commercialisation

Much of the research for the various phases of the Tui Tech project has been funded by the Welsh Government and their Technology Business Development Department – Business Wales , and numerous other business support schemes since 2019.

It was now time, in 2022/3, for DCW to take the research, ideas and proof of concept examples forward to a commercially viable conclusion starting with finding a suitable partner willing and able to manufacture and support a specialised and complex engineering and technology challenge and help us to bring it to the jewelry marketplace. Luckily for us just a few miles away (a mere five miles or fifteen minutes away, quite literally 'just down the road') from DCW's home base in Talbot Green, Pontyclun South Wales is a well-known, household name, electronics company that specialize in development design production, manufacturing and sale of electrical and electronic equipment, components and sensors. Unfortunately until all the negotiations and contracts are completed and signed off we are operating under a strict NDA so unable to name the company at this point in time.

Their specialists have reverse engineered our original proof of concept developments and made a number of improvements Figure 26 below is how the outer casings will now look (still subject to possible change and amendment).

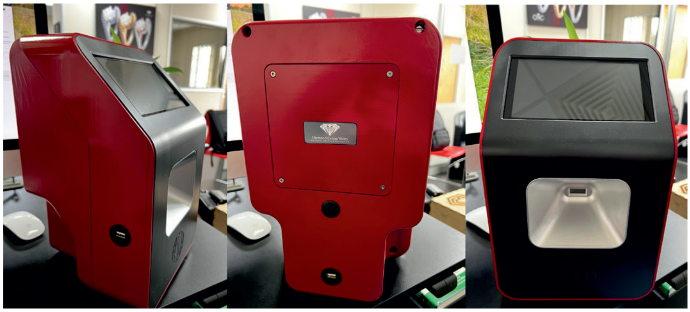


Figure 26: The Outer Casing Enclosure

In the Figure 27 below you can see the newest configuration for the two spheres.

Figure 27: The Two Spheres

As well as the enclosure and its aesthetics this manufacturing company will also be manufacturing and fitting the internal electrical and electronic components with some of their newest, best and in some cases yet to be released inventory including high end sensors, photonics and digital imagery equipment as well as a number of other components 'borrowed' from their other divisions. Such as a Raspberry Pi for the brain of the machine. And other proven and field tested electronics as used in their well-known and proven commercial consumer products.

They will also be responsible the distribution of the equipment as well as for routine maintenance and ongoing technical support for the Tui Tech units to be supplied to end users.

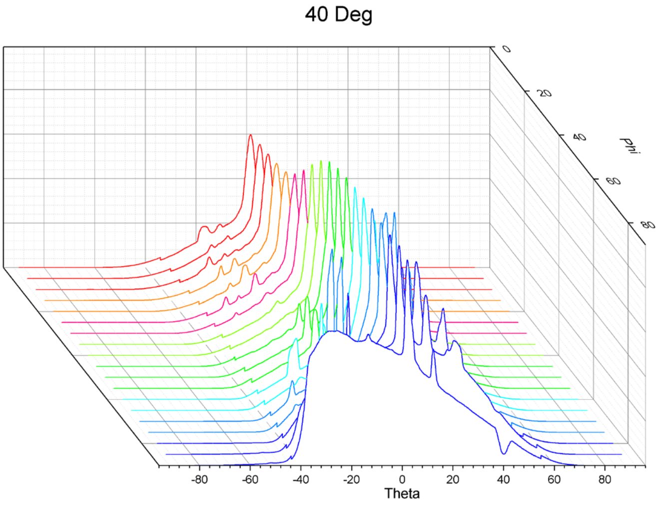
Who Might These End Users Be?

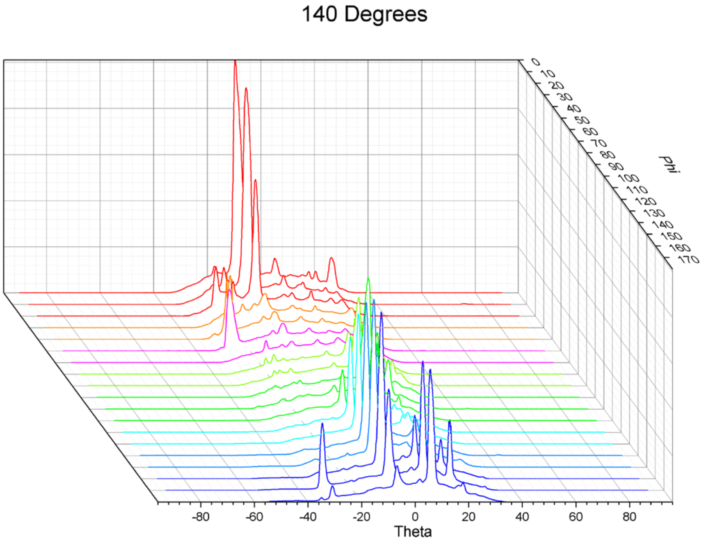
We see them mostly being used in the various Diamond Grading Labs around the world and we perceive that their main use will be for diamonds with a higher net worth from around the £1500 ($2000) upwards mark. A number of UK Assay Offices have shown interest in obtaining the technology and the UK insurance industry is also keeping a keen watching brief on progress. There will be a leasing model to supplement the outright purchase option and the equipment's users/operators will not be required to be highly skilled to use the Tui Tech technology. An app has been developed and the use of the equipment is intended to be completely digital (i.e. paperless) with a direct link to the blockchain. The internal data base of the equipment will be updated remotely, particularly with data about the origin of stones and the mines from whence they came.

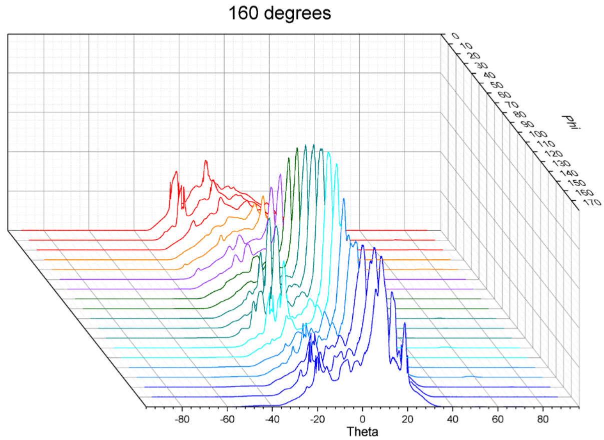
The data about the mines is to be installed in conjunction with the lead researchers at Aberystwyth university, tapping into a historical database from previous works, containing all the parameters for mined stones and their genetic composition that has been recorded and logged in great detail enabling us to cross-reference every stone TuiTech tests and matching its make-up to this pre-existing data file to give an accurate geo location of that stone creating a traceability life cycle that follows that particular stone back to its source. The Tui Tech technology is based on the pre-existing GIA standard and not intended to be a re-invention of the wheel it is simply envisioned that it should help to improve standards and guarantees of the quality of diamonds and other precious/semi-precious gem stones. The technology will bring with it the ability to confirm the quality and integrity and therefore the real value of any given diamond and add a premium transparency to it (Tui Tech will also work equally as well colored stones and of course be able to identify lab grown and treated stones).

The technology is still being developed, tweaked and de-bugged but here are some early results of tests on diamonds of known qualities based on current grading standards and their corresponding results after being measured on the Tui-Tech technology.

Results Grid







Using a goniospectrometer, light being refracted from inside the diamond was measured around the top half the diamond in a full hemisphere, with the angle of which the light was put into the diamond altered to observe how the light refracted and re-emitted out the top of the diamond is dependent on the light coming into it. The following graphs show that slight differences between 20 degrees show massive variations, and even if the light is put into a diamond via the sample angle, but the alternate side.

Data showed that shallow angles and angles close to 90 degrees (IE, going directly into the diamond from above or just off centre) produced vastly different results also, meaning a method to determine all the light at multiple core angles is essential to characterising the total light coming out of a diamond. The Sharp peaks are the light escaping out of specific facets of the diamond.

Conclusion

This is not the end of the story or of the R&D work being carried out by the DCW team.
You may be asking yourself how will the consumer/purchaser of a diamond, tested and certified by the TuiTech technology, know that the diamond set into their piece of very expensive jewelry is the same diamond as that which was tested in the machine? This is where our second technological development will come into play and which is also nearing full commercialisation in 2024.

<u>Seculuxe (Secure Luxury)</u>

Seculuxe is a laser powered technology capable of marking a diamond externally or even internally with a QR code less than the size of the period at the end of this sentence. (You can actually fit the QR code into the full stop approx. 15-20 times across its width!) The Seculuxe laser security system will be an innovative traceability and crime prevention solution to mark valuable assets on the Nano scale, secured through a decentralised database enabling traceability and security. With the use of this Nano laser security along with our Blockchain authentication technology we are able to offer a new solution that will give security and traceability to any valuable assets where this was previously not possible or easily forged, tampered with or removed. It is achieved via our novel HI-resolution Nano-marking laser, secure dot-matrix system and authentication tool, to ensure immutable traceability and protection. The system offers complete protection with the ability to produce a QR code laser marked on to any material, which is completely undetectable to the human eye and is linked to a secure database, authenticated with Blockchain technology. The unique QR code can be linked to a secure database to generate a completely traceable solution and asset recovery tool, giving a full product lifecycle and distribution ledger that cannot be altered or tampered with.

Acknowledgement

This paper has been produced in conjunction with the unwavering advice, knowledge and support of Rhys Wilson, head of research and development at Diamond Centre Wales, who has patiently checked and rechecked the work presented and kept me on the right path throughout.
Diolch Rhys

Figure 28: Rhys Wilson