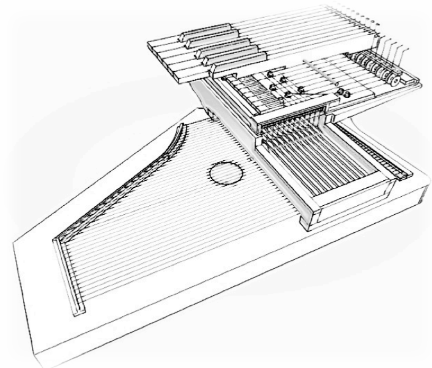
Design and Development of the Reverse Action Piano Harp Context 2 – Commission of Prototype 5 and Preparatory work



The Reverse Action Piano Harp (Raph) is a novel musical instrument interface. It consists of a bespoke zither, with playing enhanced through a secondary damping interface. Current prototypes incorporate a traditional keyboard, which provides reverse damping from individual keys, to each octave occurrence of a pitch on the string surface. The interface is designed from a conception of an ideal playing position that provides optimum access for the left hand to address the keyboard and the right hand to address the string surface.

This project has been informed through periods of practice-based research, alternating between design and build (and analysis of the results), and performance, composition and arranging (with similar reflective analysis informing the subsequent design and build phase). The project dates from 2008 and includes a patent (secured 2012) and successful PhD (completed 2015).

This submission documents the design work upon the instrument covering the relevant period for REF submission (2014-2019) but in order to provide appropriate context, brief analysis from previous prototypes is provided within Context 1 & 2 documents.

Commission of Prototype 5 Harp

In the summer of 2010 I arranged the first meet with luthier, Alec Anness, to discuss a possible collaboration. Alec has an interesting blend of skills. His original training is in woodworking; cabinet making, bespoke furniture and particularly in finishing (French polishing). He is also a musician, and this blend of skills met in piano maintenance and restoration. Alec still works in this capacity but seems to work increasingly on commissioned instruments; every time I visit, his workshop is filled with a greater number and variety of instruments. He makes banjos, autoharps and dulcimers. The testimonies to his instruments were without exception excellent, and to me he seemed the best harp maker in the UK. His special interest in the autoharp and his blend of musical and luthier skills, together with his ability and willingness to innovate, made him an excellent potential collaborator for the project.

The first aspects discussed were the acoustic properties of the autoharp itself. The quality of the three commercial harps that I had purchased was frankly, poor. This experience now constituted a reasonable spread of variation; in addition to the diatonic German harp, a Chromaharp (prototype 2) and an Oscar Schmidt chromatic harp (in preparation for prototype 3). The Schmidt harp was the best of these, but still poor when compared to even the most basic guitar that I had owned. I wanted to talk through some ideas on improving the instrument’s sound. My ideas centred around a study of guitar shape, design strategy and acoustic properties compared to the relatively small shape of the autoharp. I had therefore determined that I wanted extra volume within the cavity, better bridging and top plate shaping. Alec listened to all this politely, and simply replied that it was not necessary; citing a recent harp by D’Aigle that integrated many of the properties that I had put forward, he talked of how it changed the nature of the weight and balance of the instrument and stated his opinion that this was a shame because it was departing so far from the autoharp tradition. On testing, I had to agree. I found his harps fully lived up to expectations — they sounded astonishing compared to commercial harps. The issue of musical tradition and its relationship to community and market had become a concern by this stage of the project and I knew that there would be considerable advantage in innovating upon an instrument whose outward appearance placed it within the accepted phenotype of autoharp.

Alec was more circumspect about how he achieved this considerable improvement in sound without marked change in outward appearance; saying only that piano design was much more applicable than guitar design. Since I had not approached the problem from this perspective, and in any case all my knowledge was theoretical, I was unable to formulate the right questions to gain a significant understanding of the issues and reluctantly had to leave this question for a later date.

We first agreed that I would commission a harp from him, of unusual proportions (we agreed on 42 strings, a high D and low D and the interval break between bass range and melody range discussed in the previous chapter). Overall we spent several hours in his workshop discussing all aspects of the project. Alec was very interested in its progression. He agreed that the principle of reverse action was sound, and though not really a keyboard player, understood exactly what the successful completion of such an instrument would accomplish. He had an interesting perspective on the autoharp; he felt that the best players of the instrument (and in contrast to other instruments) were around at this point in its history and that this aspect was still developing. In contrast that there was a recognition that no one quite seemed to know how to develop the instrument further. He was reserved about the idea of taking on the making of the reverse action keyboard, feeling that whilst a lot of design issues had been addressed in the earlier prototype 2, a great deal still remained, and that it was too early to hand over from prototyping to the expense of engaging a luthier. Not least because the keyboard and damping action were still skeletal and there was a good deal of design to be done to provide a finished housing, which simultaneously provided maintenance access. We therefore agreed that I would make a third prototype, which would place appearance and finish amongst its design priorities, and we agreed to meet after the completion of both projects, at which time we would consult once more and decide how to proceed in order to finish the project.

One more thing that Alec asked was that he be allowed to keep and study prototype 2, a request to which I acceded very reluctantly, as I knew that I would be without a harp on which to engage in any musical practice for some time. It did provide a considerable spur to complete prototype 3 though.

Prototype 3

Figure 1. Photographs of Prototype 3 and Assessment of the 16 Design Criteria

Year	2010	2011
Considered in Prototype	3a	3b
Action		
1. Playing position	Yes	Yes
2. Keyboard: appearance and feel	Yes	Yes
3. Pulley and string system	Yes	Yes
4. Key pivot point to damper coupling	Yes	Yes
5. Key range	Yes	Yes
6. Harmonic damping	Yes	
7. Minimal noise	No	No
8. Integrated amplification	No	No
9. Playing space on the string surface	Yes	Yes
10. String tuning and range	Yes	Yes
11. Access for maintenance	Yes	Yes
Harp		
12. String distinction	Yes	Yes
13. Tuning mechanisms	No	No
14. Top plate	No	No
15. Depth and volume of the resonating chamber	No	No
16. Optimised coupling of bridge and top plate	No	No

No	Not considered in this prototype
Yes	Actively considered
Yes	Working, but further optimisation possible
	Parameter considered optimised or range understood

Prototype 3 was built in two intense periods of activity: the first took place in June and July of 2010, and consisted of work on the lower action (including solving the problem of harmonic damping), the pulley system and integrating a temporary keyboard similar to prototype 2. The second took place in January of 2011.

Prototype 3 was built in a mix of woods. I did not, as suggested by Alec Anness, move directly to hardwood, I considered that I was still experimenting with design, and I did not want to feel cost pressure in terms of the level of experimentation. But I did improve the quality of the softwoods that I was working with through different sourcing. The two finished top plates that you see on the damper bars and the keyboards are reclaimed from a broken guitar, acquired and de-constructed in order to better understand how the compound radius arching and simple curves of the top and bottom plate were respectively constructed (thinking ahead to prototype 6). In addition, I varnished the keyboard itself to a finish, in order to understand how this would affect its dimensions and friction.

The damping system integrates 15 bar autoharp spring mechanisms sourced from D'Aigle, which were then cut to 12-bar size, and reversed. The photograph below shows the integration of this mechanism, hinged on the bass side of the instrument such that damper bars can be removed and maintained without removing the upper action. The keyboard housing is removed in this photograph to show as much mechanism detail as possible.

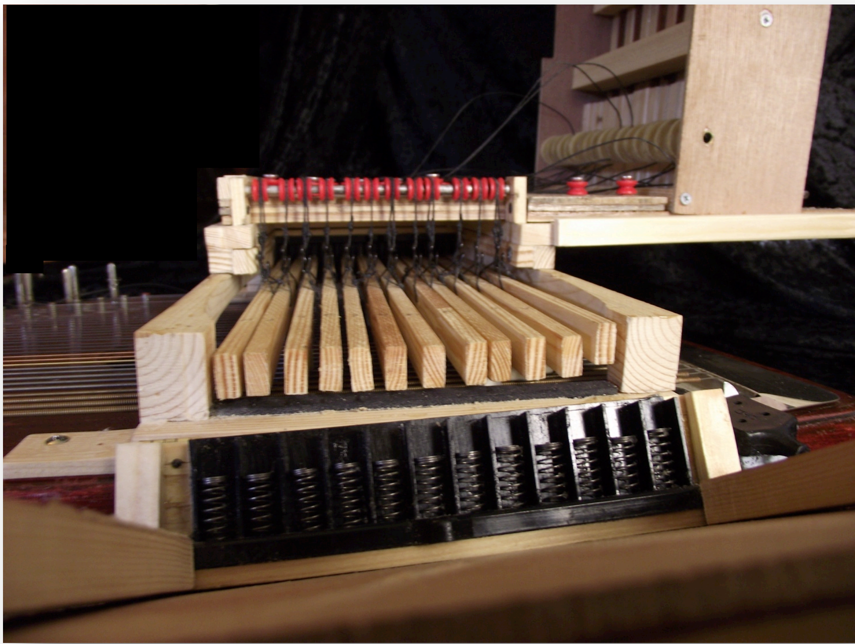


Figure 2. Prototype 3 stripped down to show pulley systems and lower action

Finalising the damper positions took about six hours over two sessions. There are 12! possible arrangements (479,001,600), which is a very large number, but otherwise uninteresting. In practice although each damper bar has 12 possible positions, many can be ruled out immediately. I proceeded by testing each damper bar in turn, recording unacceptable and acceptable positions for each, then overlaying each of the 12 diagrams in combinations and sorting through different possible solutions. Arriving at the final position remained time consuming, and there are still one or two minor harmonics remaining. Overall I felt that I had achieved comparable harmonic damping to Alec's harps, and I was pleased, when we met, that he agreed with this assessment.

The photograph right, shows the pulley system oriented from the bass side. The photograph below is from the treble side (now with the keyboard housing on). Note that the matrix pulley wheels do not now appear in a diagonal line, as they did in Prototype 2. Instead their positions are determined by the intersection of perpendicular lines from the keyboard pulley wheels and the new random damper bar order of:

C, A, G, E, B♭, C♯, F♯, B G♯, D, F, E♭.

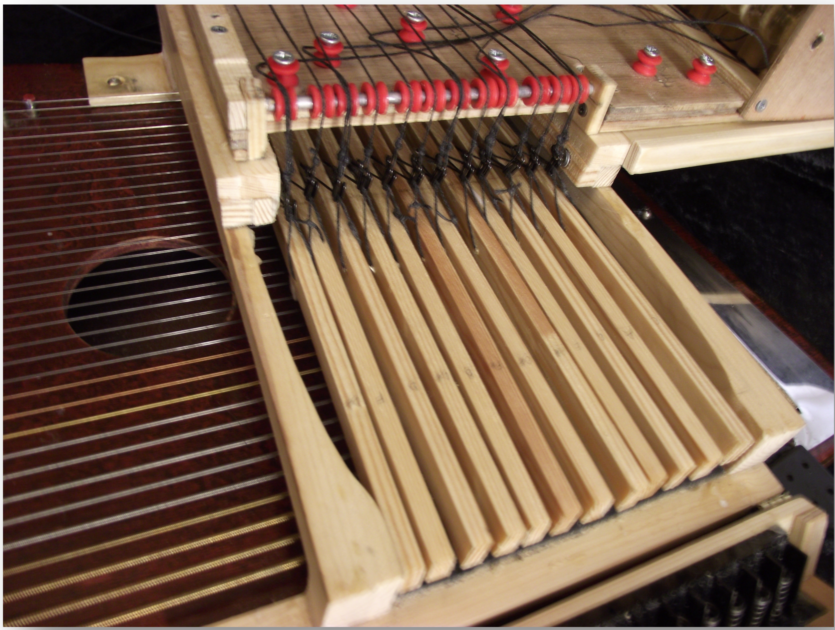


Figure 3. Photograph of the lower action (damper bar pulley system)

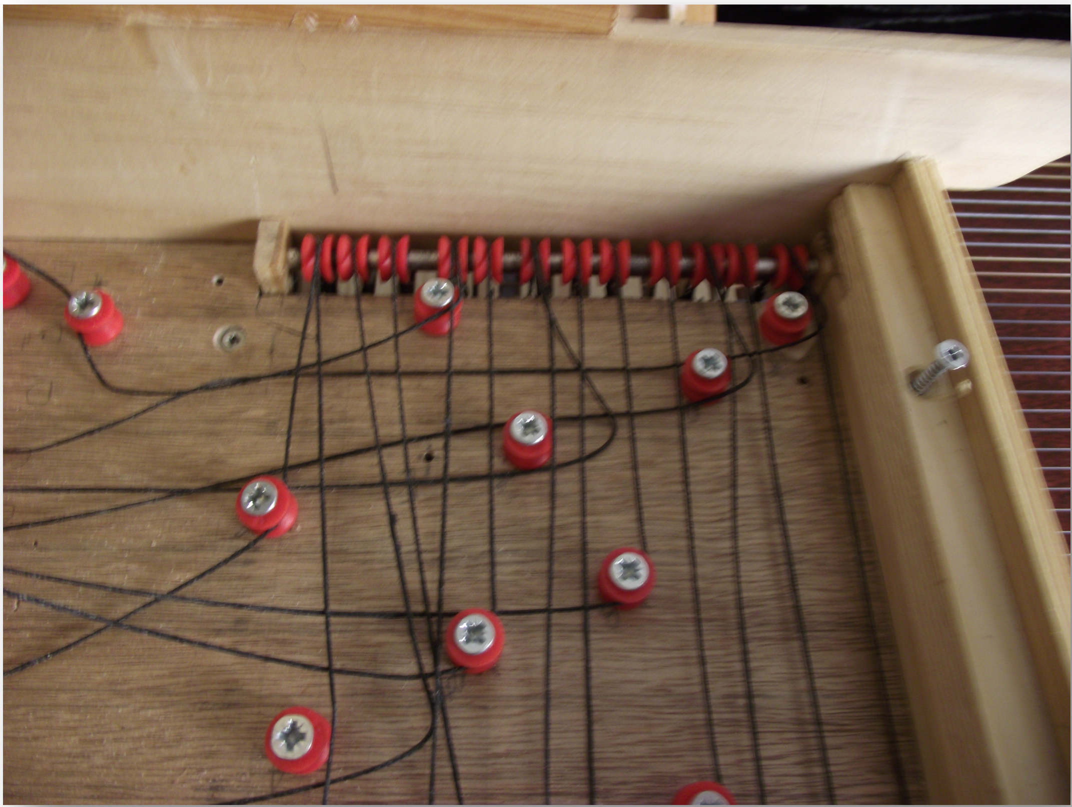


Figure 4. The Matrix & Damper Bar Pulley System

Below, the orientation is now from the toe end of the instrument looking towards the back of the keys. The keyboard pulley wheels were changed to sewing machine bobbins in this

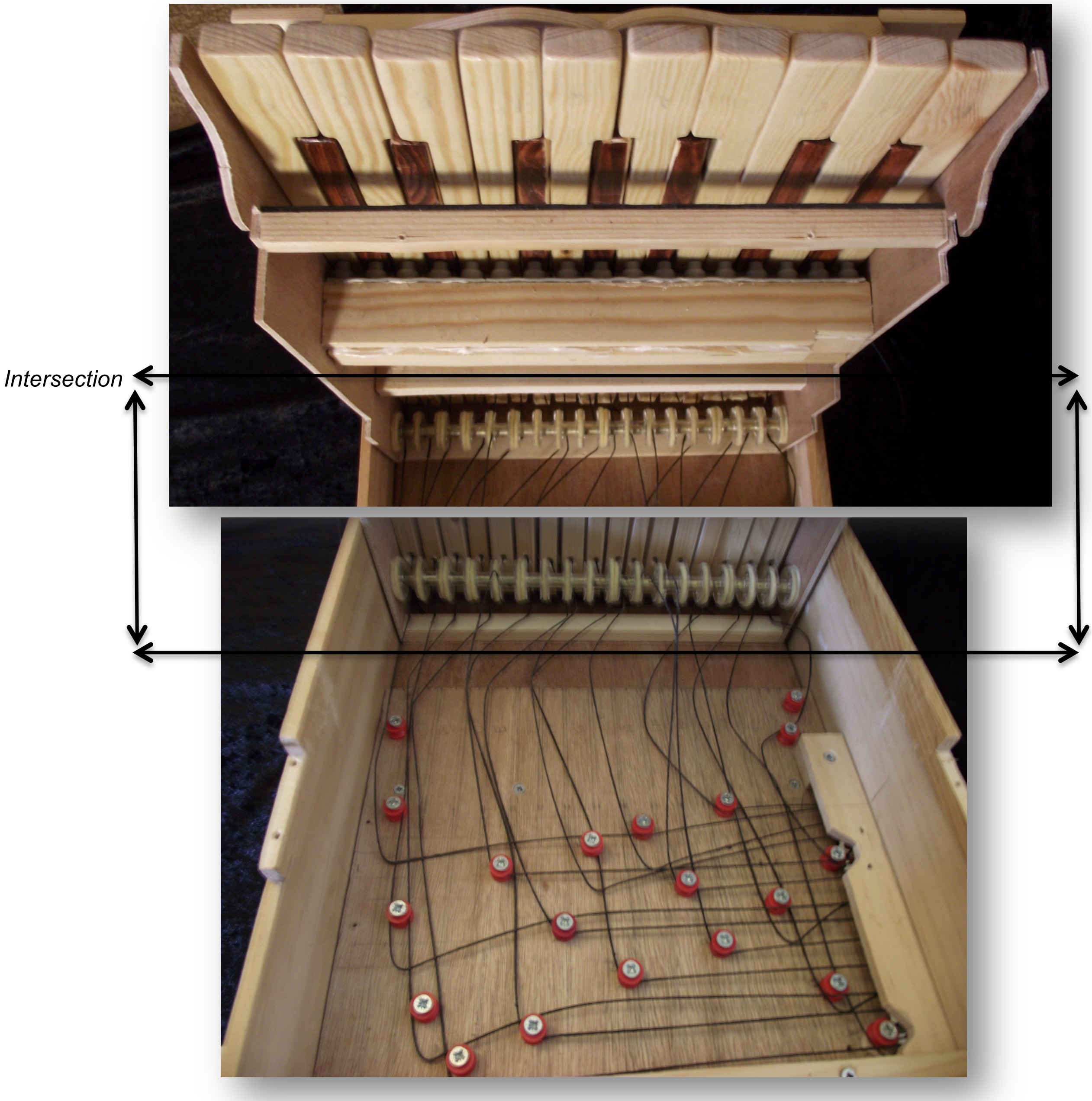


Figure 5. View from the Toe end of Prototype 3

prototype, which are a larger bore size (which results in a stronger bar), and a larger overall diameter. These are a good fit relative to the keyboard dimensions. The damper bar pulley system is now covered by its housing in this photograph. This series of photographs also shows how the action is dismantled for maintenance, giving complete access to all aspects of the action whilst minimising the effect on the outward appearance (very few visible screw points).

The dimensions for the keyboard build of this prototype were firstly considered in relation to ideal piano key size (octave span 164mm) and the size of the reclaimed keyboard that was first used to test the damping (similar to prototype 2), which is a little smaller. Given that this prototype added four keys to reach a total of 17 keys (discussed in chapter 3); thought had to be given to the added width to the rear of the keyboard which was now established within the playing position, as sitting between the legs of the player. The width of the reclaimed keyboard was acceptable, and its spacing as a playing interface, also acceptable; but I considered that there was now an added design pressure to constrain this measurement and not to allow it to expand to piano standard width (a similar pressure is exerted on the dimensions of the keyboard housing). This was the first design job undertaken in 3d rendering, a skill that developed throughout the subsequent period to the extent that I have included a section dedicated to virtual prototyping.

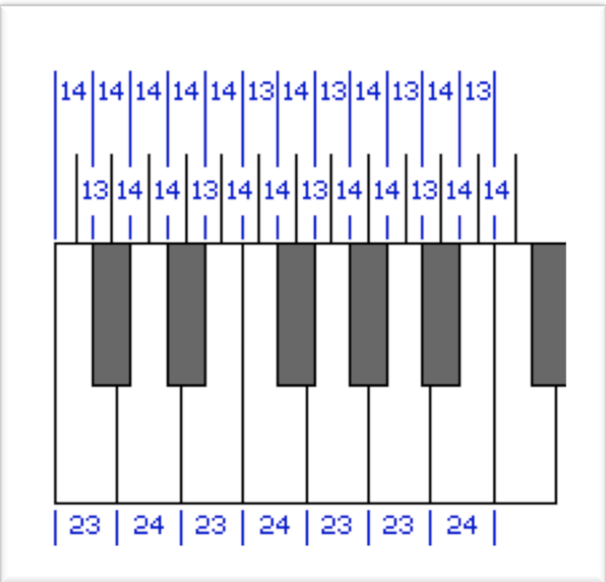


Figure 6. A Keyboard Simple Dimensions (Savard, 2007) *Status: Permission Sought*

For an excellent discussion on keyboard geometry and practical keyboard design John Savard's (Savard, 2007) discussion was invaluable. A practical solution arrived at in this document is shown left (measurements in millimetres). This solution achieves a standard piano octave span of 164mm. The design intent here is for individual key measurement to remain as whole number millimetre measurements (deemed the lowest possible for accurate hand cutting). It does not achieve complete uniformity across the white key surfaces. Instead, it preserves mirror symmetry between C and E centred on D, and between F and B centred on G♯, and allows a slight variance of 1mm between the presented white key surfaces. It does not take account of the spaces between the notes, and is slightly wider than required for prototype 3.

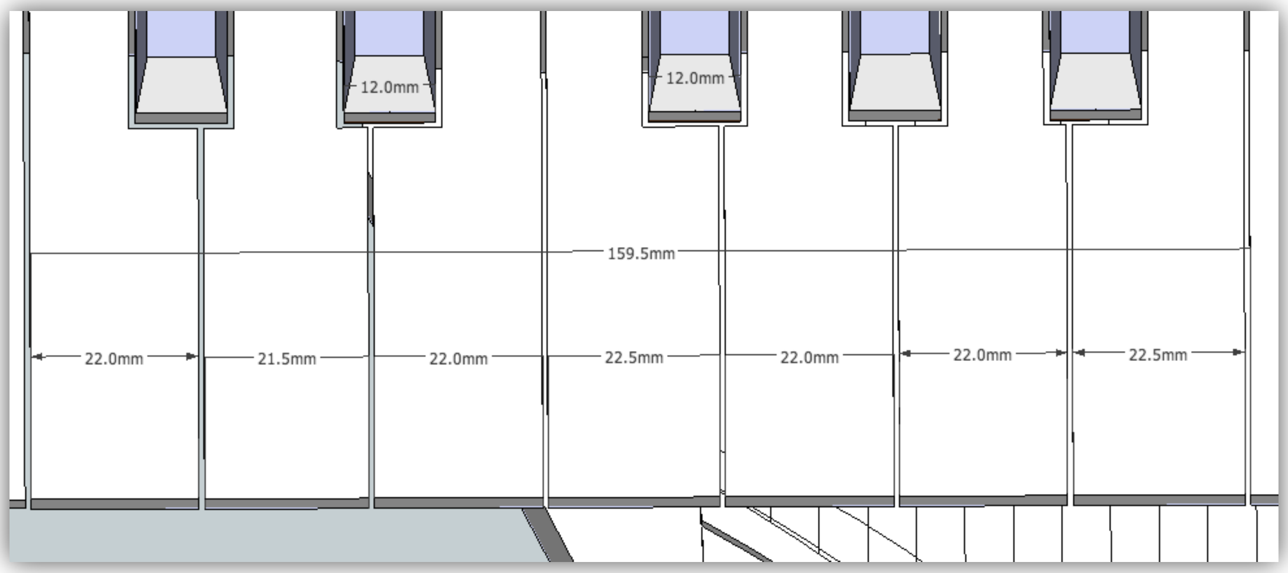


Figure 7. The Geometry of Prototype 3 Keyboard

The solution arrived at for prototype 3 (using 3d rendering) also preserves this mirror symmetry, and with the same variance of 1mm over the entire keyboard. However, in this keyboard no adjacent key varies by more than 0.5mm. The width of the black keys is 12mm. The lowest measurement allowed is 0.5mm

The sum of the white key surfaces in this projection is 154.5mm. Added to this figure are the spaces allowed between the keys, set at 0.7mm between white keys and 0.8mm black to white key. The final projected octave span is then 159.5mm — a shortening of nearly half a centimetre over standard width.

Whether or not this ideal was consistently achieved on prototype 3 is another matter, softwood is difficult to cut consistently at this level of accuracy, and the whole procedure needed to be undertaken, considered and refined. By the time the next keyboard was cut by hand (prototype 5), a series of improvements to the procedure led to a far more consistent result. Overall however, prototype 3 keyboard does fit the dimensions accurately and works extremely well.

The key springs used in this prototype are unusual silicone compression springs reclaimed from an evolution MK-149 MIDI keyboard. These can be seen in figure 4.43, integrated into the keyboard before the pivot point. Reclaiming parts from a variety of MIDI keyboards has been interesting, and a surprising aspect was that the key spring mechanisms were different in each. These compression springs were the easiest by far to integrate, and have the advantage of being silent.

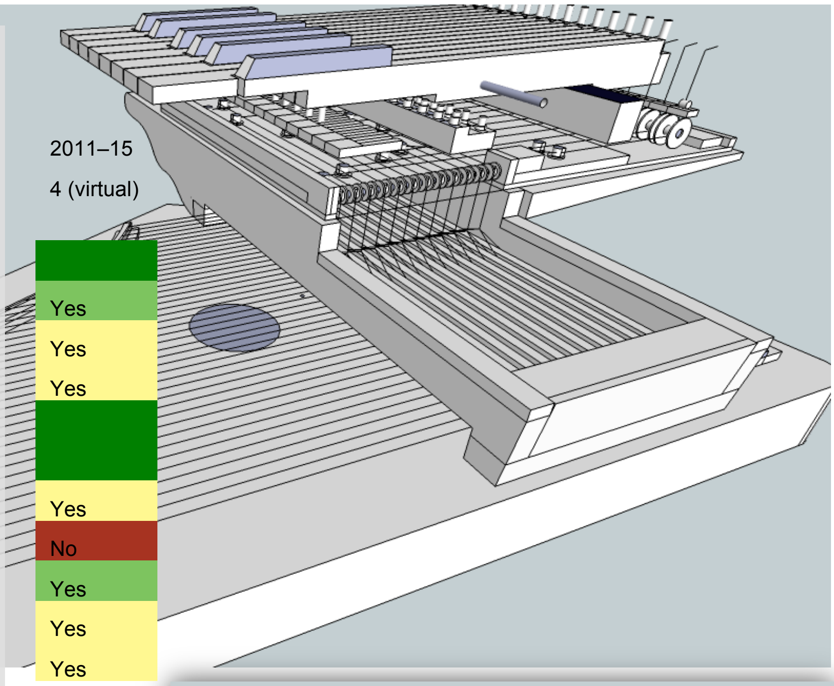
Zither pins were again integrated as mechanisms to control the pulley tension. Whilst these (once again) worked very well and were better integrated in prototype 3, they did cause problems. Within prototype 2 the 5mm zither pins were hand pushed into a borehole of very slightly smaller dimensions. They didn't provide very much resistance, but in fact not much is needed for the pulley strings. After all, they don't need to tension a string to provide a pitch. However, I did think that they needed to be properly integrated; provide a reasonable level of resistance, such that they could be tensioned using a tuning hammer, rather than by hand and not be in danger of falling out. I had talked over this aspect with Alec Anness; the pin block for his harps is made from offcuts of Steinway piano pin block, too small for use in piano restoration, but perfect for the smaller autoharps. This super-pressurised material allows him to hammer 5mm zither pins into 4mm boreholes without fear of splitting. Alas, the same cannot be said for the zither pins on prototype 3, where there were numerous problems with splitting when I attempted to hammer pins into different materials for integration at the ends of the keys. The platform is simply too small when compared to the large surface area at the toe end of a harp. In the end, I solved this simply, by clamping and gluing around the pin in each case, and though none have given subsequent trouble, I did not consider this a reasonable method for future prototypes.

Another flaw was the possibility of sideways movement on the playing surface of the keys. The reclaimed keyboards invariably provide two points where individual keys are guided in their movement once at the pivot point, and a second mechanism underneath the playing surface, which prevents sideways movement. Pianos also integrate such a mechanism. The Raph keyboard however, pivots around a bar that significantly restricts this movement, and I had wondered whether a second point would be necessary. I also felt that such a mechanism needed to be drawn accurately before an attempt was made to construct it. The keyboard certainly functions well enough without it, but I considered that there was a reasonable margin for improvement here, and determined that this aspect too would be changed on the next prototype.

The principle benefit of the custom keyboard was that it allowed the pivot point of the keys to be re-set to 217mm (as in prototype one), now recognised as a key measurement in providing correct power, and also appropriate keyboard feel to a pianist. This distance remains a compromise when compared to the two separate pivot points of black and white keys found in a piano. In principle it would be possible to create separate pivot points on the Raph, and I do consider that there would be a gain from this. It would be complicated though, and I chose not to implement this in the virtual prototypes that were to follow, or in prototype 5.

A last issue to highlight is that this prototype did consider the issue of string distinction. On the Schmidt harp the letter names of each of the strings are placed next to the zither pin. Since the pitch range (and some of the string gauges) were changed as discussed in chapter 3, a new system of distinction was called for. This was done using enamel paint on the top of each of the bridge pins such that adjacent octaves can be recognised by similarity of colour coding. I found this to be useful at times (and particularly for tuning), but that it didn't provide sufficiently clear visual distinction to be relied on, or even accessed during playing.

Overall, despite the flaws, this was the first Raph where the keyboard really felt right, looked reasonably good; where the harp was efficiently damped and was in itself a decent sounding instrument. For the first time I felt I could really develop some meaningful musical practice from it.



Prototype 4 (Virtual)

Year	2011–15
Considered in Prototype	4 (virtual)
Action	
1. Playing position	
2. Keyboard: appearance and feel	Yes
3. Pulley and string system	Yes
4. Key pivot point to damper coupling	Yes
5. Key range	
6. Harmonic damping	
7. Minimal noise	Yes
8. Integrated amplification	No
9. Playing space on the string surface	Yes
10. String tuning and range	Yes
11. Access for maintenance	Yes
Harp	
12. String distinction	No
13. Tuning mechanisms	No
14. Top plate	No
15. Depth and volume of the resonating chamber	No
16. Optimised coupling of bridge and top plate	No

No	Not considered in this prototype
Yes	Actively considered
Yes	Working, but further optimisation possible
	Parameter considered optimised or range understood

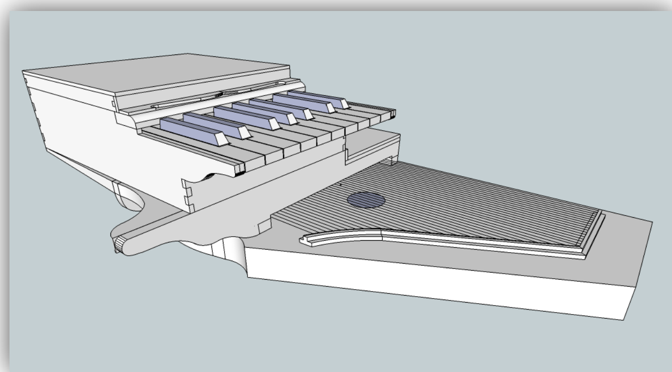


Figure 8. 3D Renderings of Prototype 4 and Assessment of the 16 Design Criteria

Though still relatively simple (when compared to, for example) a piano, I realised that the design had gained sufficient complexity by the stage of prototype 3 as to make the job of communicating the details of its construction to Alec Anness a significant problem. One option was to simply hand over prototype 3 to Alec, commissioning him to adapt it to the new harp. Alec still had prototype 2 in his workshop at this time, and I was aware that he had taken it apart and studied it, as we had been communicating regularly with reports of our respective progress.

This course of action would still present him a good deal of difficulties however; the Schmidt harp (prototype 3) and Alec's harp (for prototype 5) were different dimensions with different numbers of strings, and this would require completely new measurements for the lower action. In addition, there was no guarantee that the harmonic damping solution arrived at for prototype 3 would transfer effectively to the new harp; this job would have to be done again, and new positions on the matrix drilled for the pulley wheels. Further, though prototype 3 is a pretty tidy construction overall, it still relies on a good degree of trial and error, and layering of wood in order to arrive at the correct dimensions. This would not be satisfactory for Alec to work from — luthiers are used to working from specific plans where *all* of the parts are considered and dimensions are available. So despite the progress in prototype 3, significant obstacles to interfacing with Alec's harp remained.

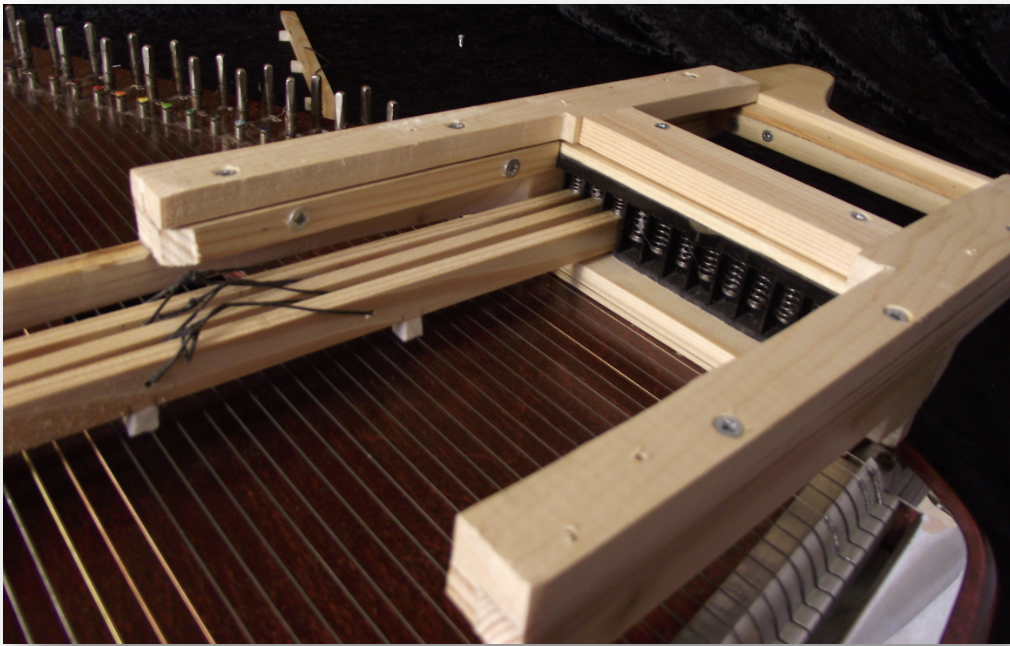


Figure 9. The Lower Action of Prototype 3

The photographs of prototype 3, lower action (above and below), illustrate this last, and most significant aspect of the problems. Looking at the area facing the toe end of the instrument, for example (the area which will sit directly under the keyboard), a quick analysis reveals that five separate pieces can be reduced to one. In addition, end grain is visible from the comb backing from the toe end, whose shape also needs re-designing.

End grain

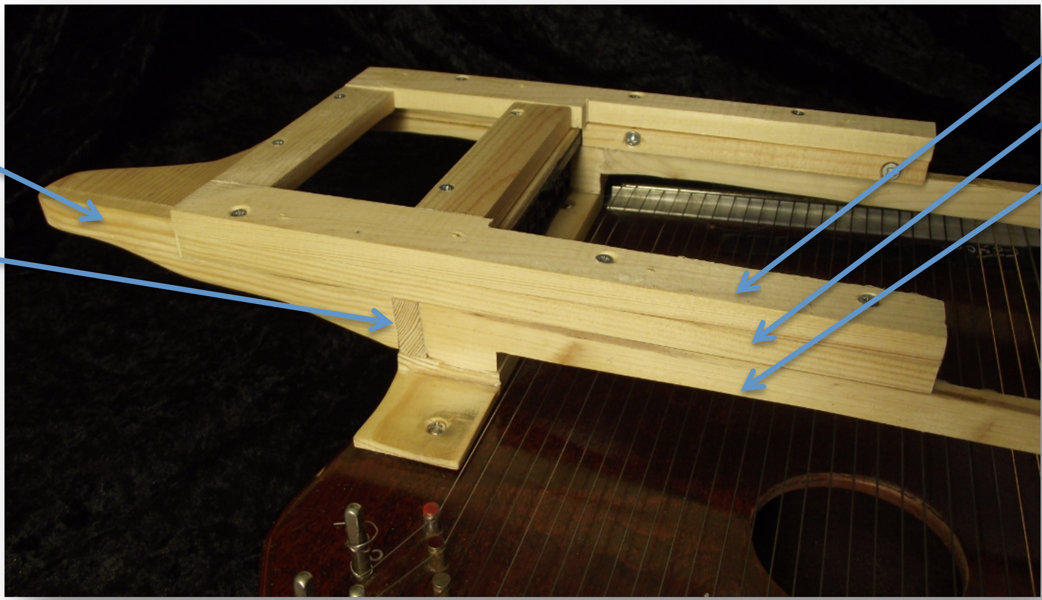


Figure 10. Analysis of parts for amalgamation

Three-dimensional rendering seemed to be a much better approach at this stage than returning to technical drawing. I had never used the technique, but I relished the prospect; I researched the options available, and spoke to various colleagues in the design workshop at University of Salford, regarding possible solutions. After some searching I settled on Google sketchup; as providing the necessary precision, the ability to print from screen at any angle, the ability to print 1:1 (or other) scale for accurate plans, and its ability to output to dxf and stl file formats, which would enable me to communicate with computer navigated cutting and 3d printing technology respectively.

Learning 3d rendering gave a richness and freedom to the practice for this project that was not previously present. I found that I have an ability to imagine well in 3 dimensions, and previously, would rather plan in this way — straight from the mind; measurements and method, than draw in 2 dimensions – I have little ability in rendering perspective accurately. However 3d rendering seemed to suit this combination of mental abilities perfectly; the detail of the measurements and angles are the means of construction and once drawn the model can be turned and viewed from any angle, and magnified at will. 3d rendering practice is, in fact uncannily similar to the reality of working with the materials.

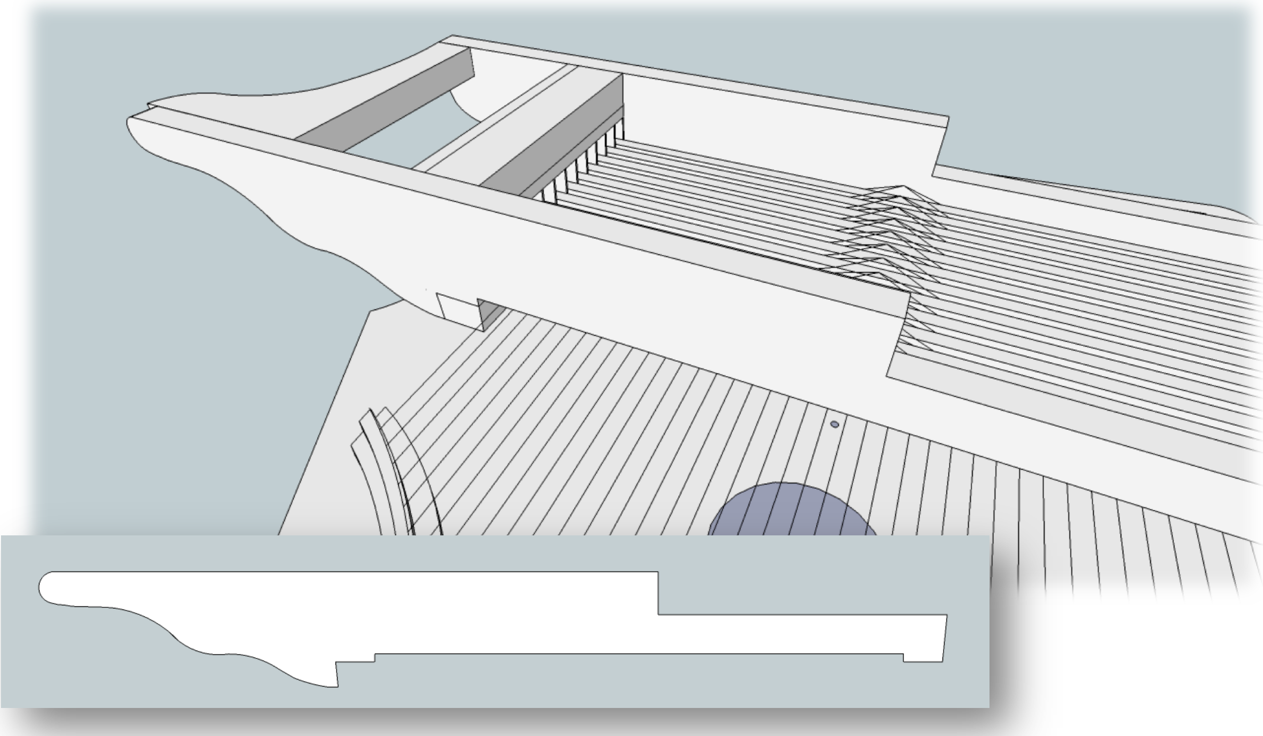


Figure 11. Five Parts reduced to one Toe Cross Spar

The rendering capture above shows a similar view as the previous photograph of prototype 3, where the five separate parts shown have been reduced to one continuous toe cross spar, with all of the different shapes and measurements that the various cuts required, captured and integrated. This single cross spar can then be printed at 1:1 (though this particular piece requires A3 to do so) or assembled as part of a .dxf file alongside all other 12mm depth profile cuts. Similar, very accurate simplification and tidying of multiple parts is present throughout the rendering process.

Having begun with keyboard design, I turned attention next, to accurate rendering of the harp bodies. I rendered the Schmidt harp first, and used this as a proving ground. The Schmidt harp proved to be quite difficult to measure. There are no sharp angles, very few right angles, no parallel lines and the strings are not parallel to any of the sides. Accuracy can be achieved though by reducing the complex curves to a series of triangles from a nominal centre point and then by changing the triangles considered. Measure – predict – compare – alter drawing, repeat; best describes the method used to achieve an accurate 3d rendering.

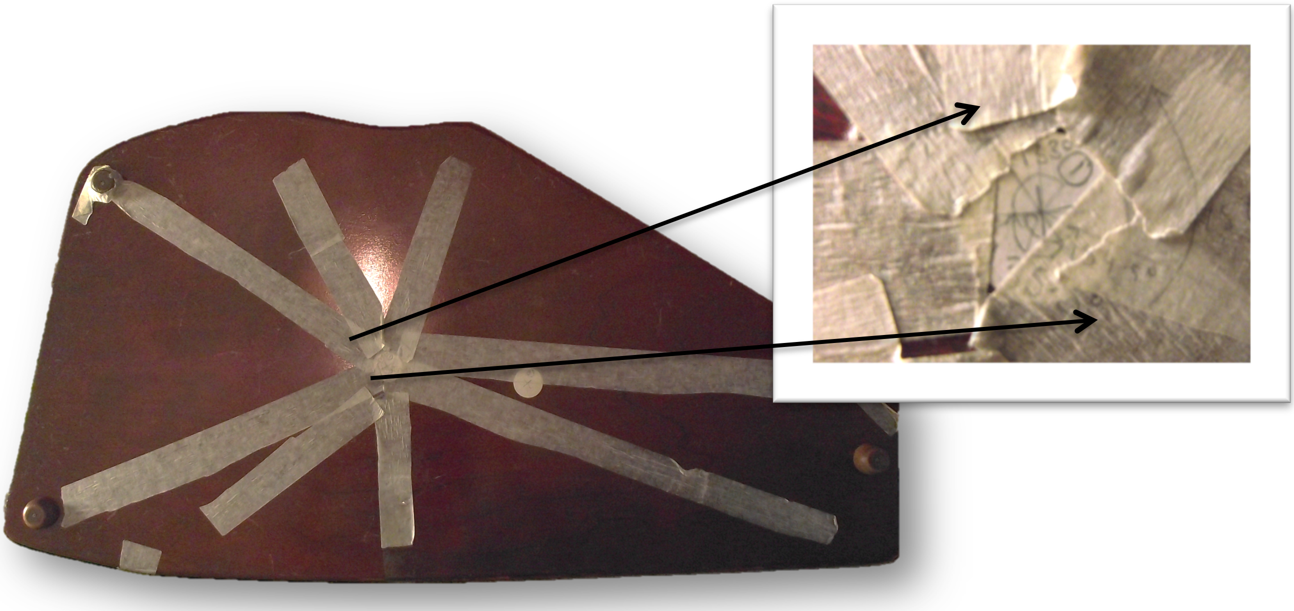


Figure 12. Illustrates the process of measuring the dimensions of the Schmidt Harp body

The capture below shows the final phase of this process, which is notable in my memory as the only time I have used trigonometry in a real life situation.

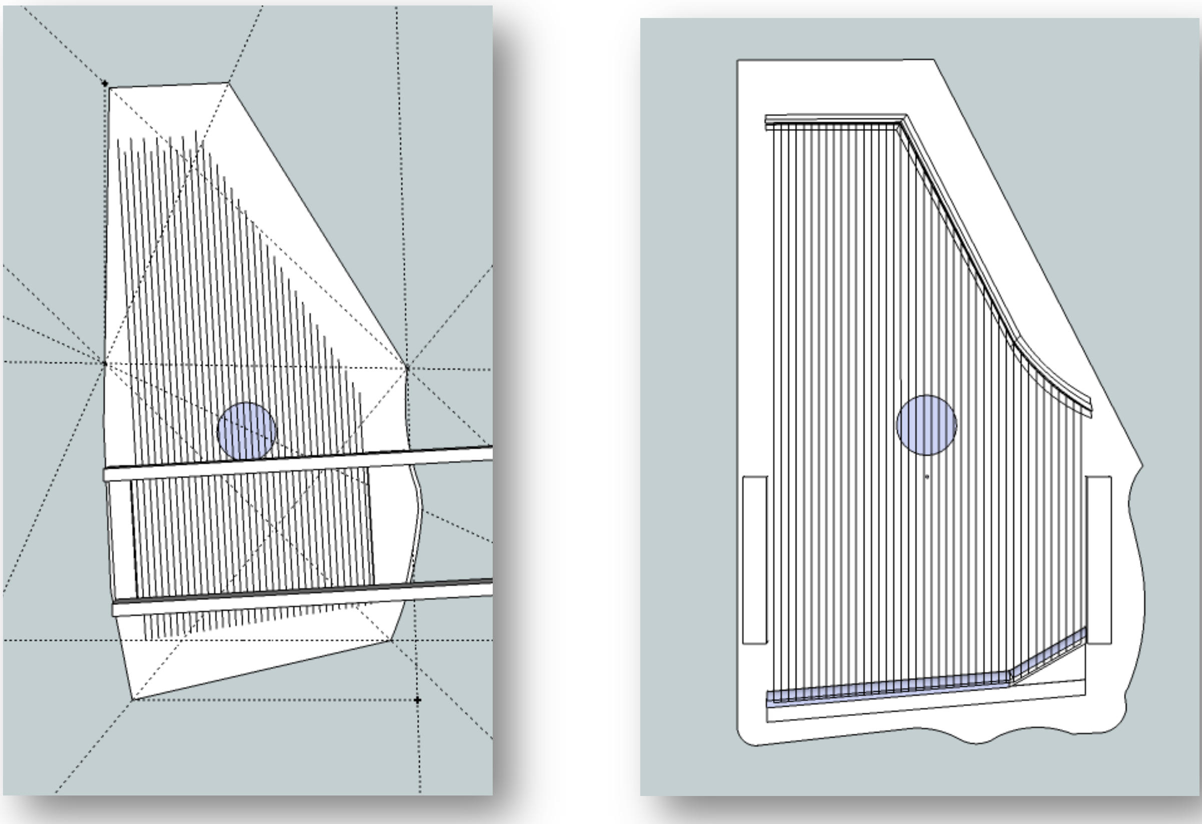


Figure 13. Final Renderings: Schmidt left (strings slightly off-axis), Annes right

A key finding of this exercise was to ensure that the strings were placed parallel to an axis within the 3d rendering software. Almost everything on the keyboard and damping action is then either parallel or perpendicular to this axis, which makes the drawing process considerably easier. Fortunately Alec's harp design was much easier to render precisely, as the strings are parallel to the bass side, which is a straight cut, and the top of the toe end is set at a 90° angle from the bass side.

There were three specific design aspects that were improved as part of the 3d rendering process. The first is that key guides were added at the front of the keys to stop sideways movement of keys (discussed in prototype 3).

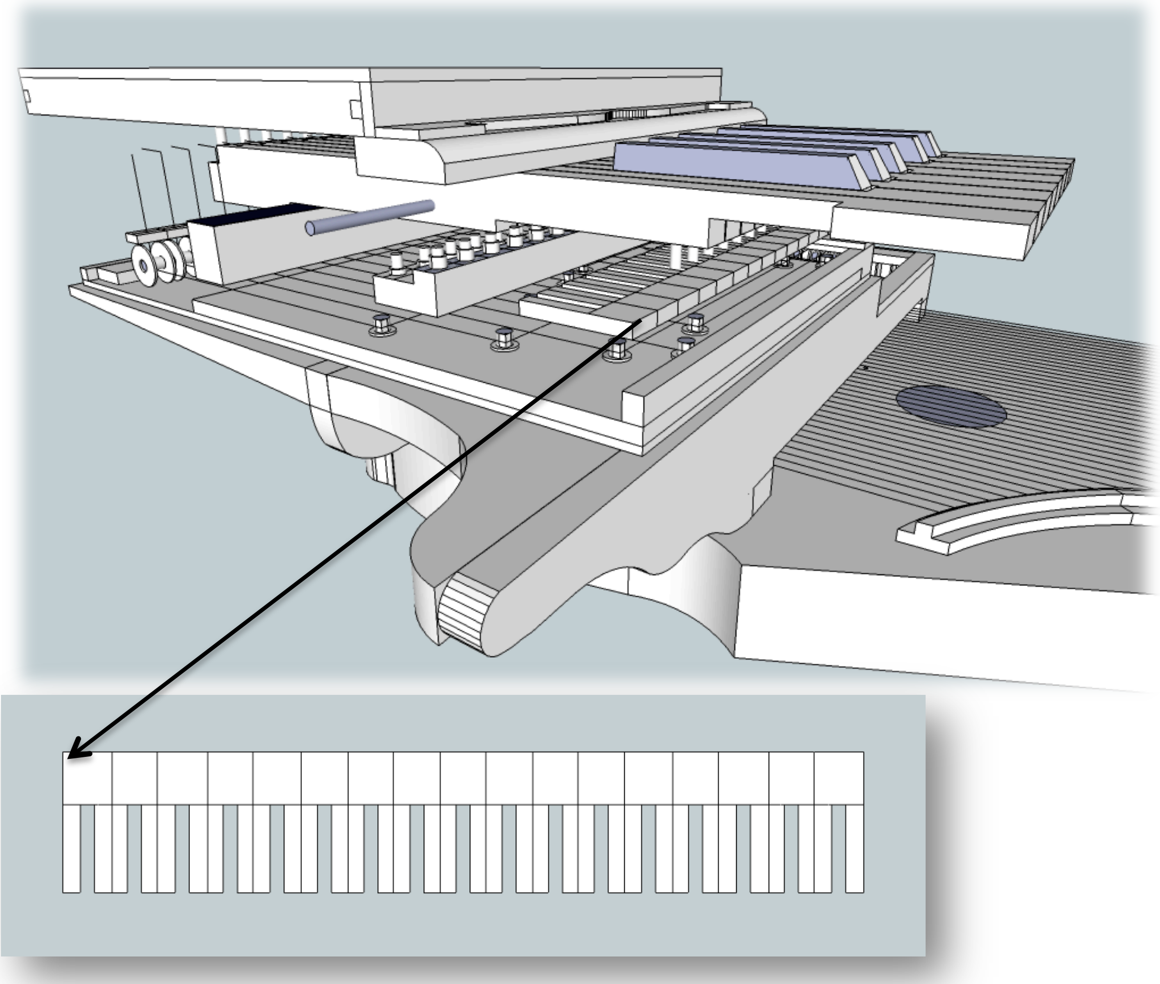


Figure 14. Cross-Section through the keyboard and key guard enlarged

This is set as close as reasonably possible to the toe end of the keyboard housing. The comb gaps are set to 4mm allowing the guides to be made from 3.6mm plywood and leave a 0.2mm margin on either side. The second change is to the keyboard pulley system. This was not moved, but its point of attachment has been changed, such that it is glued to the bass plate permanently, and is not part of the keyboard box. The keyboard is then completely separated from the pulley system in terms of separation-for-maintenance (when the keyboard is lifted the entire pulley system is left intact). This enabled a third, further (suggested) weakness to be addressed. Free key travel, before the pulley system is engaged, led several people (including Alec) to question the stability of the pulley system given that this must result in a certain amount of slackness in the pulley strings. In practice I have never considered this a problem. Admittedly, prototype 2 did (very rarely) slip a pulley string from the smaller keyboard pulley wheels, though this more often happened in transit than in playing (these pulley wheels are left accessible on this prototype for this reason). Prototype 3 (where these smaller pulley wheels were changed to larger sewing machine bobbins) never slipped a pulley string, even after countless playing hours. Nonetheless, in order to satisfy the criticism, this problem was solved through the addition of the component shown below set directly above the keyboard pulley system. The bore diameter is 3mm, which allows free movement of the pulley strings on take up from the keys, but the pulley strings are knotted at neutral tension above the bar so that any slackness in the pulley strings is constrained between this bar and the keyboard. In this way no slackness can enter the pulley system.

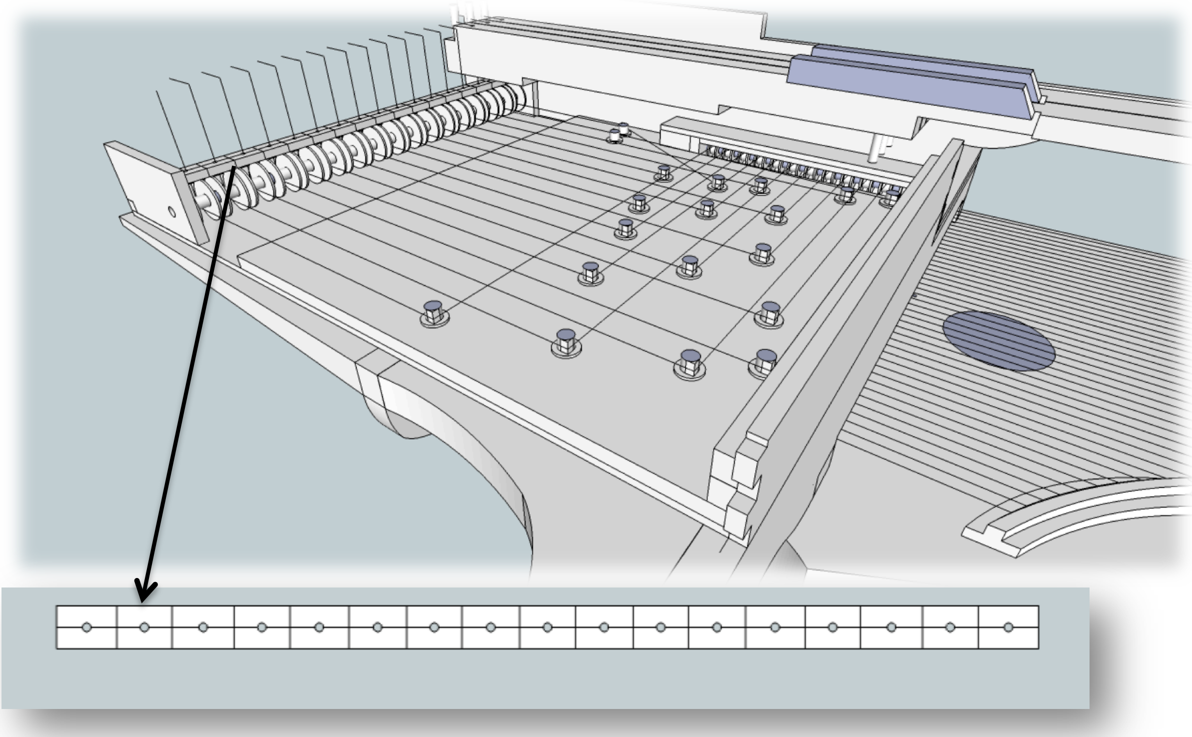


Figure 15. The Redesigned Keyboard Pulley System

Still, these three changes are relatively small compared to the changes through prototypes 1 – 3, and the majority of changes are to the precision of the overall form, reducing the number of overall parts and giving homogeneity to the overall surface and aesthetic appearance.

Considering the steady progress through the list of design principles expressed as selective pressures, it is natural that a different selective pressure emerged at this point; stasis. I felt it crucial that the gains made through previous prototypes be expressed in their most refined form for integration with Alec’s harp, and since I was essentially satisfied with the performance of prototype 3 I did not want random changes to cause unexpected problems. In the event several issues did emerge in this way; which will be discussed under prototype 5.

The completion of the 3 dimensional rendering enabled further possibilities. It formalised all of the parts that constituted the design in terms of dimensions such that templates for all could be formulated. This would enable much more effective communication of the ideas to Alec, should he wish to make the action after the completion of the harp body. Thinking ahead to wider distribution within the musical community — to reach a market (and assuming no mass production) two pathways struck me as realistic possibilities for development. Firstly, I could use this drawing to formulate and distribute a very accurate set of plans to enable a keyboard action to be built by anyone. Secondly, I could generate .dxf files to enable the same set of plans to be cut on a CNC. Both of these methods are accepted means of distribution for early adoption within innovation technology.

Manuals and Flat Pack Harps

Despite the distraction of these patent exchanges, I continued to make progress on creating an accurate build manual. I planned to get as far as the lower action, and then to take a joint decision with Alec as to whether or not this was a reasonable way for the project to be progressed. Alec announced his completion of the harp body at the end of March 2012, and we arranged a meet for the end of June, by which time he had received a draft of the lower action manual. The manual is included within this document at Appendix 3 and consists of a method section with 3 dimensional views, and a complete parts schedule with measurements and 1:1 printing without annotation for template purposes. It is also included in the digital assets that accompany this written document in its original .pdf format.

I received feedback from Alec on the manual at this meeting, and had also received feedback from other colleagues and most helpfully from my brother Ian Brissenden who works in aircraft design. Ian's feedback particularly called for a tighter approach in terms of parts description, rendering, and method, feeling that this was part of the process he termed *manufacturing engineering* "a specific view where tooling is specified and built around the model [arrived at the *as built — maturity C stage*], any jigs are designed here. They are not aircraft parts but still form part of the configuration as the final parts have to have traceability to the tools and jigs" (Brissenden I. H., 2011). I agreed with all the criticism, though I felt that there was some misunderstanding over the purpose of this particular version of the manual (it was after all, designed specifically for Alec, to be accompanied by prototype 4, and to serve as a starting point for discussion rather than a complete manual from scratch), but it helped me to pinpoint the differences in the approach that I had taken, and exactly what was needed for a "from scratch" approach. Overall, I felt that I had demonstrated that I had overcome the most significant technical problems involved and that such a manual could now be produced as part of a strategy of market distribution, should this be determined as a desirable option.

In the event, it was Alec's reaction to prototype 3 that decided the subsequent workflow. He quickly took in every aspect of it, turning the whole thing over and examining the build quality and finish from every angle. He appeared to be very pleased with it. Prototype 2 was set out ready for the meeting, in his workshop — I hadn't seen it myself for several months, and I had significant appreciation of the change he was seeing. I had been concentrating so much on the virtual prototype, engrossed in the improvements between this and prototype 3 that I had quite forgotten the really significant change from prototype 2 to 3, particularly in the issues that had most concerned Alec, which were to do with the quality of the build and the overall finish. By the time we had finished discussing all the changes, including dismantling prototype 3 to demonstrate the access for maintenance, and going through the manual and the 3d renderings, Alec was encouraging me to take control of the build of prototype 5 myself, saying that only the finishing (French polishing) should be left to him. Alec pressed me on two issues: firstly, to be sure that the dimensions of the new plans exactly matched the dimensions of the plans that he had sent me, and secondly, that I could print all of the parts that I was describing at 1:1, to provide templates. When I reassured him on both counts, we agreed that I would complete the action for prototype 5 and that he would finish it.

In the autumn of 2012 I explored the possibilities for interfacing the design with computer navigated cutting, and completed this process in an intensive period in January 2013. The workshop at University of Salford has a laser cutter, and two small router based CNCs. The laser cutter was suitable for profile cuts up to a depth of around 5mm, but had the disadvantage that it left burn marks on the wood. The CNCs contained in the workshop at the time were really too small for the number of profile cuts which were necessary for the project. After some research, I found another option, which was to use the Fab Lab situated within Manchester. Fab Labs are a worldwide movement initiated by the Massachusetts Institute of Technology in 2001 (wikipedia, 2012), which aims to empower local communities by providing access to all kinds of physical rendering devices including 3 dimensional printing, laser cutting, computer programmable sewing machines and many more. There are currently 134 Fab Labs worldwide and one of these is situated in New Islington just ten minutes walk from Manchester Piccadilly train station. The Manchester Fab Lab houses a large flat bed CNC that was perfect for the harp project, and I signed up for and completed the initial training on this piece of equipment.

File preparation for cutting required classification of parts of similar depth, rendering each of these in simple profile with drill points and producing arrangements of the parts-of-similar-depth suitable to be cut from one continuous plywood sheet in separate .dxf files. Examples of the .dxf files are included in the digital assets that accompany this project, and can be viewed by accessing the accompanying pdf files. These illustrate how this process looks at the design stage. This file preparation was an extremely time-consuming process, but was necessary irrespective of whether or not the final hardwood cuts were to be rendered on a CNC or by hand, since it would allow me, for the first time, to order accurate hardwood pre-cuts with confidence.

A key issue in minimising cost on a CNC is that of cutting margins (how much space to allow between parts on a wood sheet), and unfortunately the advice on this was rather inconclusive from all quarters. Between 2 and 3cm seemed to be the consensus — dependent on the depth and type of cut being attempted. The problem was that CNCs are not often deployed in either the Fab Lab or UoS settings to cut expensive hardwood. The issue of margins is less crucial when cutting plywood sheets (the most common material) and the simple advice is to err on the side of caution, and to allow larger margins in any doubtful case, in order to maintain the structural integrity of the material sheet as a whole during the cutting process. In order to gain an understanding of this issue, I tried very hard to minimise this cost at plywood level, which made the process more time consuming. A second issue, which complicates the final arrangement of parts further, is that of grain direction — again not crucial on plywood cuts, where concentric wood sheets are laminated at perpendicular angles. Because the grain direction was not crucial on this occasion, the arrangements that you see in appendix 4 are a compromise between optimising the area for maximum yield and achieving correct grain direction for outward facing parts. This was most confusing, and the issue requires vigilance at every level of entry to the system, the initial drawings, rendering to .dxf, entry into the CNC computer and finally orientation of the wood in the CNC table — it is possible at each point to reverse the axes by mistake. I remember mid to late January of 2013 as almost continuous drawing, and redrawing together with days spent nursing plywood sheets at the cutting table at Fablab Manchester. Unfortunately the grain direction on the 9mm cut was set erroneously at one stage of the process (I am unsure which) resulting in cross grain on the playing surface of the white keys. This was one of the last cuts of the final session, and unfortunately fatigue caused me to miss this fact at the time, and so I failed to repeat the cut. Subsequently a colleague in the workshop at UoS offered to recut this in slightly thinner plywood using the laser cutter. But, as if to demonstrate how difficult this issue is to control through the entire process, made a similar mistake and the resulting keyboard surface was cross grained once again! This is a minor, non-crucial mistake in plywood but the consequences of such a mistake would be quite different in hardwood.

Figure 16. Trimming and sanding the output from CNC and laser cutter (Brissenden P. G., 2012)

Time constraints at the end of January marked a halt to these processes because there simply wasn't time to spend at Fab Lab during the teaching semester, and this gave me a chance to study the materials that had been produced and to take stock of the situation.

The photograph above shows me working on these materials, and set against the wall behind, you can see the raw output from laser cutter (left — defined by the characteristic burn on the wood) and right, from the CNC. Below shows close ups of the two different outputs within the original sheet (left) and after removal, trimming and sanding (right).

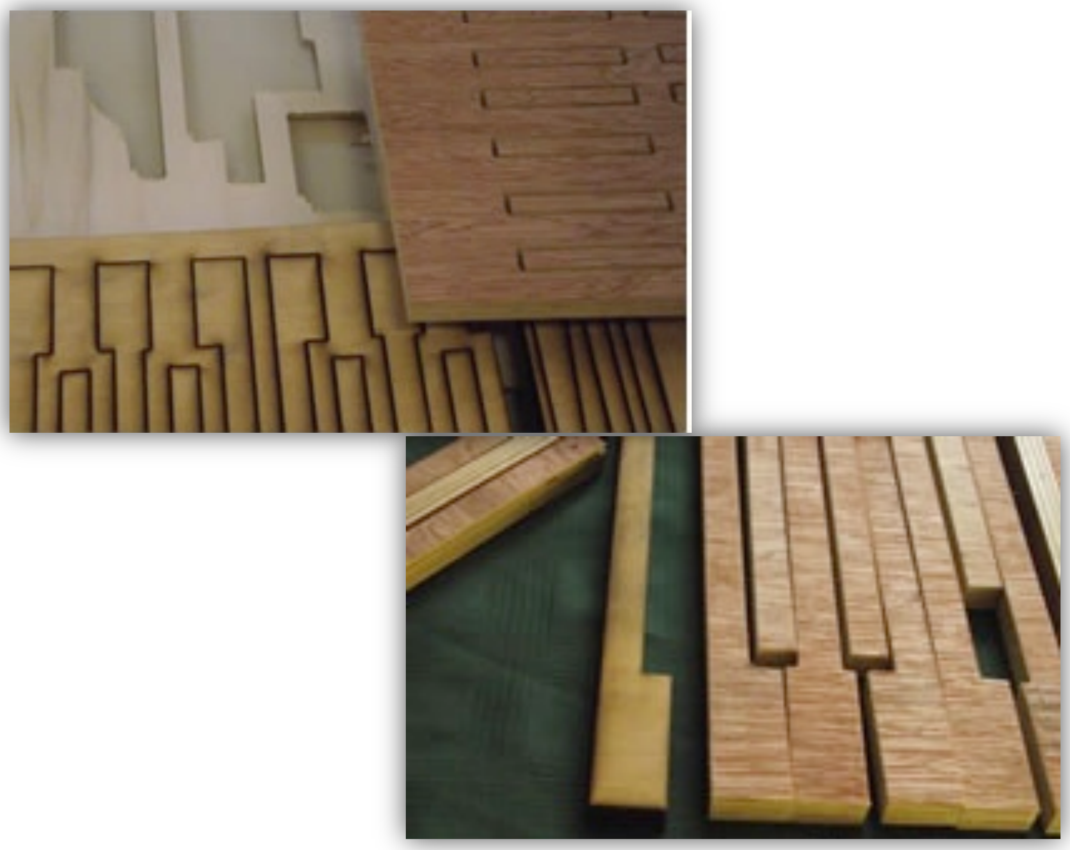


Figure 17. Outputs from CNC and laser cutter compared (Brissenden P. G., Reverse Action Piano Harp, 2013)

Neither process is the clean output that I had imagined, and both outputs take quite a lot of work in order to arrive at the precision of 0.2mm that is the stated accuracy of the machines; further there is the possibility of breakage in removal of delicate parts from the outer wood.

The spring of 2013 was taken up with preparation of recordings and the publishing of a website. The website contains aspects of both design and music, but I have considered it under the next chapter of musical engagement. I returned to the question of the prototype 5 build immediately after this, and decided not to return to Fab Lab immediately. The decision was an easy one to take after reflection.

1. As with the build manual, I considered that enough experience of the medium had been gained to enable wider distribution, should this be determined to be a desirable course of action
2. Further engagement was likely to remain prone to error; and this error, coupled with the issue of the large margins necessary to work with automated cutters, as opposed to a band saw was likely to prove frustrating and expensive
3. Many of the inside parts could be used directly on the project — only outward facing parts really needed to be rendered in hardwood
4. Where rendered parts were not to be directly utilised, they would provide concrete templates to work from by hand. I discovered that these were much more useful than 1:1 paper prints
5. Based on the experience, I was not sure that the automated processes saved time overall, given all the possibilities for error and the travel involved
6. Cutting of parts is but one process in completing the action as a whole and arguably, not even the most time-consuming.

Thus the virtual rendering segued seamlessly into the build of prototype 5, which began in earnest in the summer of 2013.

Works Cited

wikipedia. (2012). *Fab Lab.* Retrieved 2012 from Wikipedia: https://en.wikipedia.org/wiki/Fab_lab

Brissenden, I. H. (2011). Analysis of Prototyping Process - Comparing your Harp to an Aircraft.

Brissenden, P. G. (2013). Retrieved 2014 from Reverse Action Piano Harp: reverseactionpianoharp.com

Brissenden, P. G. (2012). *Philip Glen Brissenden.* From Soundcloud: https://soundcloud.com/phil-brissenden/debussy-clair-de-lune

Savard, j. (2007). *The Size of the Piano Keyboard.* Retrieved 2010 from Quadibloc.com: http://quadibloc.com/other/cnv05.htm