Design and Development of the Reverse Action Piano Harp – Context 1 Early Prototypes and Analysis

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.

A Pianist and an Autoharp — A Context for Innovation

Back in the 1970s, when I was a teenager, I loved the piano and practiced it obsessively. But even in those days there was something missing — there are, give or take a few, and depending on the type; 230 or so strings inside that instrument, but somehow I could never quite get at them, could never feel in contact with them in the way that I felt that I should be able to. I did feel that sense of "direct contact with the sound" when I played the violin or the guitar, but I struggled to reach a reasonable standard on violin (I never could stand my own tuning!) and I did not (and do not) really get along with the guitar interface.

It was in this setting that I had my first encounter with a twelve bar Schmidt autoharp. Though short, it left a vivid memory. The instrument looked so much like a small piano soundboard, and at once I felt that it should provide an effective “guitar equivalence” for a pianist, sacrificing one hand in order to gain direct contact with the strings, and sacrificing complexity for portability.

I played the instrument, I loved the immediate and complete changes of chord that it gave and the gratifying changes of timbre that contact with the string surface provided — of course the chord choice was very limited, but surely you could easily change the chord bars? I attempted some melody. A problem: the over damped system did not allow the melody notes that I wanted over the chords, did not seem to allow anything in fact, other than the members of the chord itself. If you wanted another note, you had to change chord. Still, I was not immediately put off, and continued to experiment with the harmonic textures it created.

I grew aware of a second problem; a significant one from my piano perspective; the slick changes of chord very quickly sounded repetitive, and try as I might I couldn't seem to vary the texture as I wanted. Some things, change of register for example, were almost too easy, other things such as stabs and more open-space textures, with silence, seemed impossible to achieve, in fact it felt like the instrument created a momentum of its own. A piano just stops; the second that you allow the sustain pedal up, but ceasing to play this instrument, even for a moment, seemed to cause it to create a cacophonous racket by itself; it just wouldn't shut up!

I fell in love with the potential and possibility the autoharp presented, but I understood the limitations of the instrument and why it couldn't react effectively to the pianistic technique that I had developed. I studied how it worked and saw that because of the over-damped system on which it relied, it was only superficially adaptive to pianistic technique.

Various sources agree on a definition of an autoharp — the following: *a kind of zither fitted with a series of sprung and padded bars which allow the playing of chords by damping selected strings* (Oxford Dictionary) is typical. The definition consists of two components; the "harp" is a fretless zither consisting of a plurality of strings strung over a sound board. "Auto" refers to the damping mechanism where sprung damper bars damp strings extraneous to a particular chord.

Figure 1. Autoharp by Oscar Schmidt, Model No. 15a dating from 1961 (Harrison, 2004) with permission

The autoharp is an outstanding interface if the intent of the player is diatonic harmony. Slick changes of harmony can be achieved without significant technical investment on the part of the player, and it lends itself to genres that demand rhythmic accompaniment. Achieving melodic, or combination of melodic/harmonic playing upon the instrument is significantly more difficult.

Players certainly do push the boundaries of the instrument however; in this recording Bob Ellis (Ellis, 2010) demonstrates that he is able to achieve significant freedom in his melodic/harmonic combinations. He achieves this (in addition to very accurate right hand technique) through tuning/spacing compromise. His autoharps have only four chord bars, and his diatonic tuning system provides a series of doubled notes across the compass. This has two effects: firstly the spacing between the discrete pitches in the melody range is increased, providing greater potential for accuracy; secondly, a missed note is not a disaster of dissonance when it does happen. Ellis demonstrates that he is able to ornament melody with harmonic combination effectively. He also discusses the drawbacks of the approach — the instrument plays only in two keys, D and A — a significant limitation when interacting with fiddle players, as Ellis clearly likes to do. With a resigned shrug, midway through the clip he produces a second autoharp set up to play in C and G.

At the other end of the spectrum in this recording Will Smith (Smith, 2012) plays a Chopin Nocturne on his 24 bar autoharp. The timbres are certainly unusual and the playing at times is beautiful, but also contains missed notes, and damping problems (which sound rather like poor piano pedalling). Smith comments after the clip that the chord bars are completely non-standard.

Each approach illustrates the possibilities and limitations of the over-damping system of the autoharp. Ellis achieves melodic/harmonic freedom, but at a price — the instrument is clearly limited in terms of genre engagement by the range of harmonic/melodic possibility. Smith achieves a greater tonal ambition — but at a price of great esoteric complexity in interface.

Surely a Keyboard?

The paradox is that the autoharp interface is initially extremely rewarding to the learner, and therefore very attractive to a beginner musician, but more complex musical combination demands a very significant advance in technique, which few players accomplish. Manipulating twenty-four chord bars in order to produce melodic/harmonic combinations is a feat of technical mastery. Additionally, the technique gained, is locked-in to the esoteric complexity of manipulating damper bars designed for harmony, for another purpose — that of melody/harmony combination. This results in a technical perspective that is rather different from mainstream musicians, and somewhat isolated.

The pianistic perspective on this interface observes that there are only 12 semi-tones in the Western equally tempered scale, and we have an interface (a keyboard) that will accommodate this, ready developed; needing only to be adapted effectively to the autoharp. It would allow access to *all* note combinations providing complete harmonic possibility (24 chord bars is quite simply an unacceptable starting point for a pianist). It also has the potential to allow for effective melodic playing in combination with harmony.

However, we must bear in mind that a considerable strength of the autoharp chord bar arrangement is its essential simplicity from both a mechanical and functional perspective, which leads to a practical, portable instrument capable of considerable timbral variation because the right hand is in direct contact with the strings (a quality lacking in the piano). The chord bars perform a limited musical function — they do not seek to isolate individual strings, and do not distinguish pitch height (octaves); this precision is given by the right hand in contact with the strings.

If the aim is a keyboard equivalence of this arrangement, a typical keyboard/string instrument design strategy of one key coupled to one string is not a good starting point, because the large amount of keys (matching the quantity of strings) will immediately dominate the instrument, removing the focus from the right hand in contact with the strings. In producing such an arrangement we would be well on the way to turning the instrument back into a small piano (there are extant instruments which do provide this kind of interface such as the Dolceola shown below). (Harrison, 2004)

Figure 2. Dolceola dating from around 1920 (Harrison, 2004) with permission

Instead we create an effective keyboard equivalence of the function by creating an innovation that follows these principles:

1. Keys are passive; they do not produce sound by themselves — they simply release dampers.
2. A single key is linked to a single reverse-damped bar which damps all octave occurrences of the pitch.

To give a practical illustration of this system; if I depress the key of D (this would make no sound in itself), and then strum right across the string surface of the instrument — all of the D strings would sound — but no others. If I release the key then the instrument immediately damps itself. This arrangement maintains the responsibility for articulation of individual strings to the right hand — in direct contact with the strings. From the perspective of a pianist this interface approximates and enhances that offered by an autoharp, giving reasonable and logical prospects for harmonic/melodic combination, and providing damping behaviour that conforms to keyboard expectation.

The most straightforward aspiration of this study in its entirety is the establishment of this inventive step and to establish the resulting instrument within a musical community. It is best encapsulated (in refined form) by the patent claim re-write that I provided to the UK Patent Office on 9th August 2011[1].

Claims — Reverse Action Piano Harp (Raph)

"Integration of one octave of full sized piano keys oriented towards the toe pin block parallel to the string raised at least 10cm, to provide a left hand keyboard position adaptive to pianistic tradition and right hand strumming/plucking position adaptive to autoharp traditions through use of a pulley string system connecting piano keys to reverse sprung damper bars, damping octave occurrences of individual pitches." (Brissenden P. G., 2012)

Figure 3. Playing position on prototype 3 (Brissenden P. G., Reverse Action Piano Harp, 2013)

The most significant design concern was to create comfortable playing positions for both hands, and the given resulting parallel keyboard position, a pulley and string system is the most obvious coupling mechanism providing the necessary flexibility. Other keyboard positions might provide more direct coupling options, but the optimum keyboard position takes design priority. By the time of the writing of this version of the claims it became clear that this design aspiration should be expressed as evolutionary (and adaptive) to the strengths of both traditions; that is, the adaptive potential and technical strengths of both pianistic and autoharp traditions are identified and preserved within their separate domains.

The keyboard position on the harp is the fundamental starting point. It was subject to much pre-build experimentation and discussion. The experimentation constituted playing a great deal of air-harp — taking an autoharp and imagining different keyboard/string array arrangements. The position arrived at is determined by constraints learned from

1 This claim is best suited to state the aims for this study, however it was not the version finally accepted by the UK Patent Office.

experience of piano and guitar; the keyboard position must allow a relaxed left arm, supported from the shoulder and the upper arm, with no twist in the wrist joint and the strum position must allow free forearm and wrist movement, similarly supported by the upper arm and shoulder.

Introduction

This contextual document explores the artefacts that comprise the Raph design, keyboard and string array in detail, interrogates each, and examines the potential in related musical instruments to influence the design. We arrive at precise notions of optimum configuration, and range of variation at its conclusion. This exploration proceeded contemporaneously with prototyping practice, and whilst it is not the purpose to detail prototyping here, in two cases it is necessary to understand the problems encountered in prototyping in order to assess the potential in related forms. In each case we will document prototype progress from the perspective of the design meme-set itself, focussing on musical problems of interface rather than overtly discussing the detail of the design changes and compromises that resulted: these are the meme-set of *keyboard* as applied to the string array, and evolution of the *string compass and pitch set.*

Autoharp Evolution

The invention of the autoharp is commonly credited to Charles F. Zimmermann of Philadelphia. A US Patent 257808 was granted in1882. Zimmermann certainly contributed much to the popularisation of the instrument in the United States of America, but the instrument that he produced and popularised was based more closely upon the design work of Karl Gütter. Ivan Styles' "The True History of the Autoharp" is considered the authoritative historical re-construction and Styles unhesitatingly credits Gütter as the true inventor (Styles, 1990, pp. 1–3).

A comparison of the patent drawing submitted by the two supports this view; (Zimmermann, 1882)

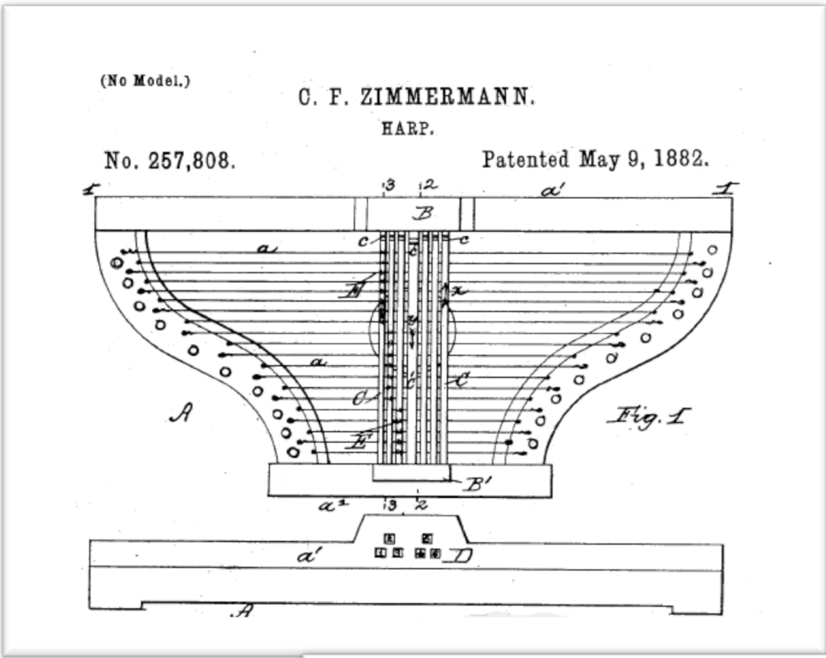

Figure 4. US Patent 257808

(Zimmermann, 1882)

Status: Public Domain

Zimmermann's drawing conceives chord bars, which damp *between* the strings by *pulling the damper bar sideways*.

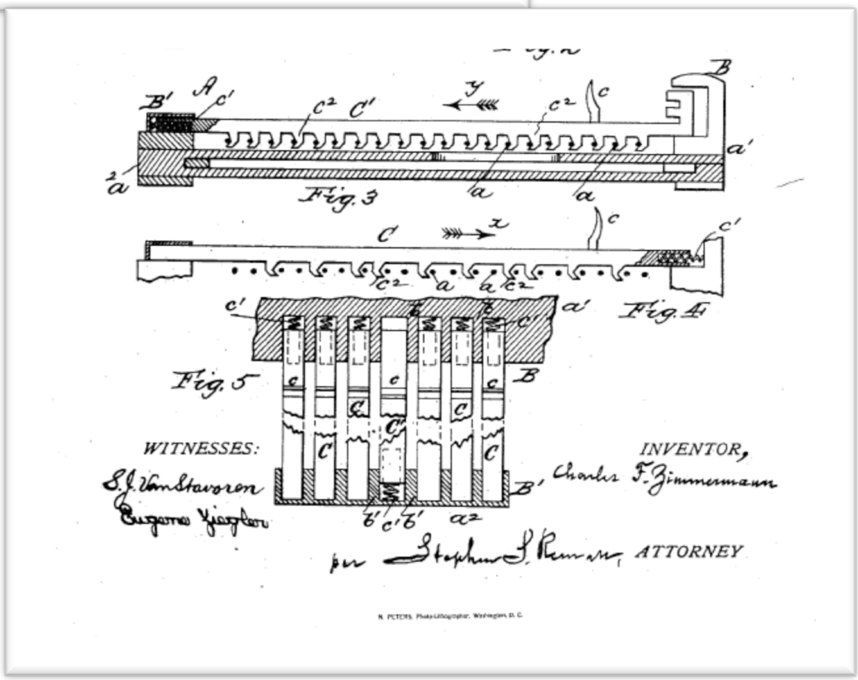

Figure 5. US Patent 257808 (Zimmermann, 1882)

Status: Public Domain

Figure 6. Zimmermann playing his own invention (Styles, 1990)

Status: Public Domain

A photograph of Zimmermann playing a version of this instrument is also produced within Styles' article.

However there are extant examples of the instrument that Zimmermann actually produced (photograph right). This is a type 1 Zimmermann production model dated at c. 1885–88, it is a diatonic tuning in the key of C, with three chord bars providing IV, I and V7 from the *toe* to *dead*[2] end of the instrument.

Figure 7. A Type 1 Zimmermann production model (Harrison, 2004)

With permission

The instrument here is clearly the same as described in the Gütter patent. Styles reproduced these original drawings from his research in the foreign patents section of the US patents office. (The drawings of this patent remain absent from commonly available online databases, and this image is reproduced directly from the Styles article (Styles, 1990).

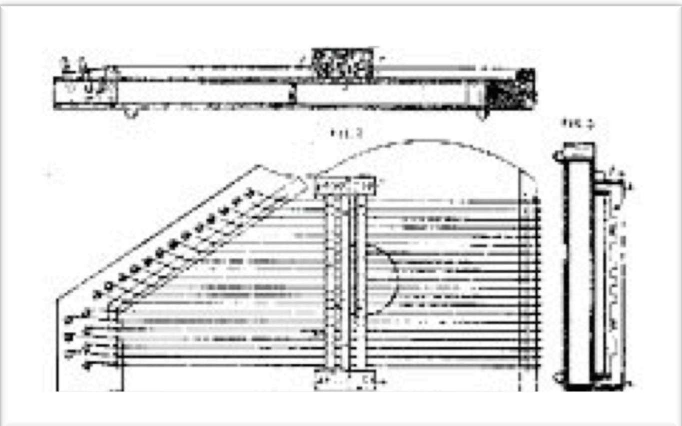

Figure 8.

Karl Gütter's original patent drawing (Styles, 1990)

Status: Public Domain

Styles identifies a trip to Germany as a source of Zimmermann's knowledge of this

[2] The toe end is shaped to string length. The tuning pins are at the toe end. The dead end is usually straight, although it can be angled or contra-shaped to string length to optimise the playing surface. Later models add fine tuning mechanisms at the dead end of the instrument.

instrument. He speculates that Zimmermann might have felt this design to be easier to manufacture than his own.

The design is certainly a more straightforward playing interface; note the playing position in the Zimmermann photograph — the instrument is placed horizontally upon a hard surface rather than held. Whilst there are some autoharp traditions that still use this playing position, precise and virtuosic players more commonly hold the instrument against the trunk of the body, and strum across the surface. This is a far more natural strum/pluck position.

Zimmermann subsequently manufactured Gütter's design under the auspices of his own patent. This sleight of hand was challenged by Herman Lindemann, a German manufacturer who had bought the rights to Gütter's design in 1883. Lindemann issued a statement in 1890 “Warning: I warn hereby especially not to buy or sell the recently sold instrument under the name of Chordzither or Autoharp that are in the market as imitations of my patent ‘Volkszither’, but the challenge appears to have come to nothing.


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Warnung!

Ich warne hierdurch ausdrücklich vor dem **An-** und **Verkauf** der seit einiger Zeit unter dem Namen **Chorzither,** auch **Autoharp** in den Handel gebrachten Nachahmungen meiner **patentirten Volkszither** (Deutsches Reichs-Patent No. 29930) und bemerke, dass ich bereits Anzeige bei der Staatsanwaltschaft gegen den **Verfertiger C. F. Thierfeld** wegen Patentverletzung erstattet habe, alle jene Personen aber auch zur Anzeige und Bestrafung bringen werde, **die sich mit dem Verkauf dieser Nachahmungen befassen.**

Klingenthal, 7. October 1890.

H. Lindemann,

Alleiniger Fabrikant der patentirten und privilegirten „Volkszither“.

Figure 9. Lindemann’s warning notice posted in Der Zeitschrift für Instrumentenbau (Journal of Instrument Construction) (Michel) Status: Public Domain

Figure 10. Meinhold Autoharp with secondary crooks for damper bars (Harrison, 2004) with permission

The first commercially available autoharps had extremely limited chord choice, and the instrument was at once subjected to selective pressure to extend its chromatic capability. We can trace three lineages of design thinking to allow this. One lineage saw autoharps produced with increasing numbers of chord bars, examples of 15 bar and 21 bar autoharps became common; this is the standard contemporary design approach, and these types of autoharps are by far the most numerous.

Another approach introduced a further set of secondary damping control to the system. The Meinhold autoharp (above right) is one of the more straightforward examples. The twelve chord bars can be crooked a semi-tone in either direction, immediately increasing the chromatic potential. The Victoria autoharp, perhaps the closest formulation to Zimmermann's original, is another example of this. Unlike the maximised chord bar approach, extant manufactured examples are limited to 19th-century examples; though these are relatively numerous.

A third approach is to integrate a keyboard in a way similar to the Raph. Examples of such instruments do exist, but are exceedingly rare.

Keyboard Morphology

There are some features of the keyboard, that whilst perhaps not features of the (keyboard) lock-in are nonetheless, decidedly strong expectations that we have of keyboard instruments, and we begin with these because it gives us a general sense of what we think we mean when we speak of a keyboard from a musical perspective.

Dimensions

We generally expect keys to be of certain dimensions. There is a range of key size that to the eye and to an extent the player appears "full size", and this is wider than we might expect. Smaller keys do exist on musical instruments but our tendency is to think of these as toys, or starter instruments for children; the accordion (and possibly the melodica) are exceptions to this.

Historically, keyboard dimensions have varied considerably (125mm–170mm one octave span). Modern pianos present much less variation, but still vary between 164mm and 165mm (Bean, 1999).

Appearance

We generally, though not always, expect a black and white shiny surface to provide contrast, and we commonly refer to notes as "white" or "black" notes, and irrespective of the actual contrast provided by an individual keyboard (for example many harpsichord keyboards depart from this convention) we understand what we mean by black notes and white notes.

Feel

Though keyboards differ, we expect them to fall within a range of resistance provided through a sprung or weighted mechanism, and we expect a key to return automatically and speedily to rest. The amount of resistance always falls within this range — too little and the lack of resistance is disturbing to the player, whilst too much resistance affects the player's ability to play fast.

Kendall Ross Bean defines the current manufacturing standard for pianos as 50 grams key tip weight for minimum depression (Bean, 1999). This is not consistently achieved, and its application results in varying dynamic response across piano manufacturers. There is, as you would expect, even more variation across MIDI keyboard manufacturers, perhaps because there is less pressure to conform to stricter piano dimensions.

Because of the mechanical action of the hammers, piano keys need to deliver considerable power, and therefore pianists have a particular expectation regarding the pivot point of the keys, which is much longer than the size and shape of the playing surface would suggest. Because the black keys are further back, this results in two separate pivot points, for white and black keys, in order to deliver similar power in each case. The overall distance is shortened slightly for the black keys relative to the white keys, which allows for the fact that the most common playing areas are closer to each other than the overall playing surface suggests; we tend to play white keys close to the black keys (shortening the pivot point), and we tend to play on the ends of the black keys — as close to the white keys as possible (maximizing the pivot point). This slight shortening and maximizing of the pivot point results in similar key-lever ratio, and from a playing perspective, evens out the overall feel of the keyboard. Whilst the design constraints described are consistently applied, the pivot point does appear to vary across different models (between the range of 215–220mm).

We expect the keys to drop approximately 1cm, again, this can vary slightly depending on the mechanism that the keyboard is coupled to. However variance too far from a narrow range around this measurement is disturbing and affects performance. I derived this measurement empirically through measuring a number of varying keyboards with attractive actions, prior to designing the keyboard for prototype 2. Kendall Ross Bean defines the optimum as 3/8” (9.525mm) (Bean, 1999).

Lastly we generally expect individual keys to trigger a sound through means of its coupling to the sound producer (though free reed instruments do not conform to this principle).

Considering the range of keyboard application, there is a high degree of consistency in the presented playing interface across different keyboards. Pianos, organs and harpsichord particularly, display good consistency in terms of dimensions and weight. However, there is recent interest in variation of key size, and this is relevant to this study. The practical research appears to show that pianists with smaller hands benefit considerably from 15/16 and 7/8 sized keyboards (Boyle & Boyle, 2009). There is one current piano manufacturer, Steinbuhler & Co, Pennsylvania making both upright and grand pianos in these formulations. In principle it would be relatively easy to vary the dimensions of a keyboard as applied to the Raph according to the requirements of the individual player.

Keyboard Expectations Applied to Earlier Prototypes

Despite the basic nature of the workmanship within prototype 1, there was some good design thinking behind the keyboard to action coupling, which allowed for a great deal of testing flexibility in the way that the keyboard coupled to the damper pulleys.

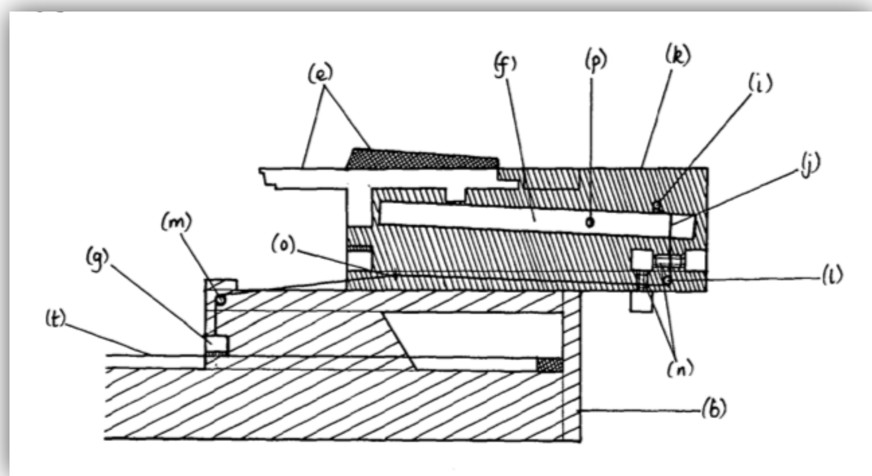


Figure 11. Patent Drawing showing the keyboard to damper bar coupling

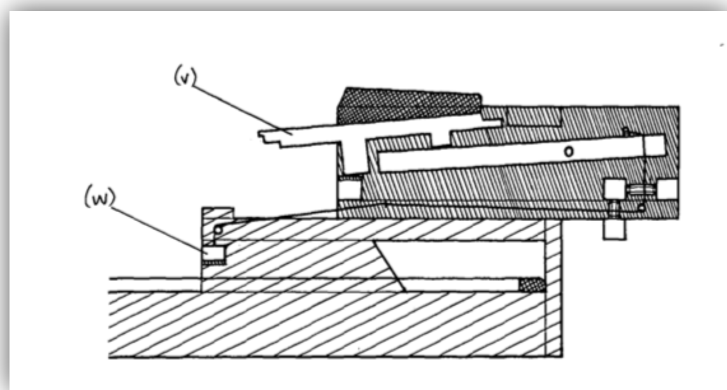


Figure 12. Patent Drawing (with key depressed)

Key to Drawings

(a) Toe pin block
(b) Dead pin block
(c) Bass rail
(d) Top rail
(e) Keyboard
(f) Wooden key rod
(g) Damper bar
(h) Spring mounting
(i) Peg
(j) Pulley string
(k) Keyboard housing
(l) Back lateral bar (pulley-wheel)
(m) Damper bar pulley-wheel
(n) Pulley-wheel
(o) Eye
(p) Pivot point
(q) Spring
(r) Washer
(s) Damper bar felt
(t) string
(u) Key crook
(v) Key depressed
(w) Damper bar raised

The drawings above show the keyboard to damper bar coupling. The keyboard was designed to move independently of the key rod, each had independent pivot points and the keyboard could be moved in relation to the damper rods, providing a range of exploration, both in terms of function and to provide a keyboard feel within the range of expectation for a pianist.

Experimenting in the first instance in complete ignorance of previous inventions, the key aspect explored in this prototype was the *key to damper coupling* (4), establishing firstly that reverse damping was possible, secondly, that it was possible for keys to release dampers (and that they would return to damp the strings effectively) and thirdly, that the instrument behaviour would be as predicted and that the musical improvements claimed, which until this point had been theory only, would be possible to achieve.

With regard to the key to damper coupling; the direction of force at the key tip (down) is opposite to that required at the damper bar, so it is logical to design a key that acts a lever, with the pulley string coupled to the far end of the key such that the upward force is in the correct direction. A pulley system, which couples this force to the damper bar, is then relatively easy to envisage.

Designing and integrating into the Raph, a keyboard that falls within expected range is key to capitalizing on pianistic technique; a keyboard player – particularly a pianist has certain expectations of a keyboard.

How far do the dampers need to be raised from the strings in order to release them? The release distance must allow sufficient space for the string to vibrate freely without encountering the damper felt. Autoharp design suggested that this distance might be comparable with the 10mm key drop. However, I felt it possible that that the high clearance found in autoharp design might have more to do with providing an adequate feeling of movement for the left hand interface and that smaller movements would be possible. A calibrating range might be between 2 and 4mm.

As discussed above pianists have a particular expectation regarding the pivot point of the keys, which is much longer than the size and shape of the playing surface would suggest. The pivot point appears to vary across different models between the range of 215–220mm.

217mm was selected as a starting measurement in the experimentation on prototype one. If the distance from key tip to pivot point is known, and the desired drop at the key tip also known (10mm), it is then possible to establish a calibrating range in order to test various possible lever ratios from key to damper bar, by providing various experimental drill points. The aim was to establish a keyboard feel within the range of expectations of the player (50g key tip weight, 10mm drop, immediate key return), which results in sufficient damper bar movement to enable free string vibration. Where the key drop is 10mm and the distance from the key tip to pivot point is 217mm:

$$\frac{10}{217} = \frac{y}{x}$$

Where y is clearance from the damper bar in mm and x is the distance from drill point on the far sider of the key rod, to pivot point.

$$\frac{10x}{217} = y$$

$$x = \frac{217y}{10}$$

$$x = \frac{2\times217}{10} = 43.4mm\ distance\ when\ y = 2$$

$$x = \frac{3\times217}{10} = 65.1mm\ when\ y = 3$$

$$x = \frac{4\times217}{10} = 86.8mm\ when\ y = 4$$

What about the force acting on the springs? Again, the two measurements necessary for the keyboard are known. Where the ideal key tip weight is 50g and the distance to the pivot point is 217mm:

$$Fx = 50\times217$$

Where x is the distance from the pivot point on the far side of the key and F is the force required at the spring.

$$F = \frac{50\times217}{x}$$

$$F = \frac{50\times217}{43.4} = 250g$$

When the damper clearance is 2mm.

$$F = \frac{50\times217}{65.1} = 166.6g$$

When the damper clearance is 3mm.

$$F = \frac{50\times217}{86.8} = 125g$$

When the damper clearance is 4mm.

This assumes that the damper bar springs will provide the force necessary to return the key, but another unknown at this time was the resistance a pulley and string system adds to the system – particularly a primitive pulley and string system such as that of prototype 1, and further, whether the key return would be sufficiently rapid, so as to feel natural – originating as it would, from such a removed point in the system.

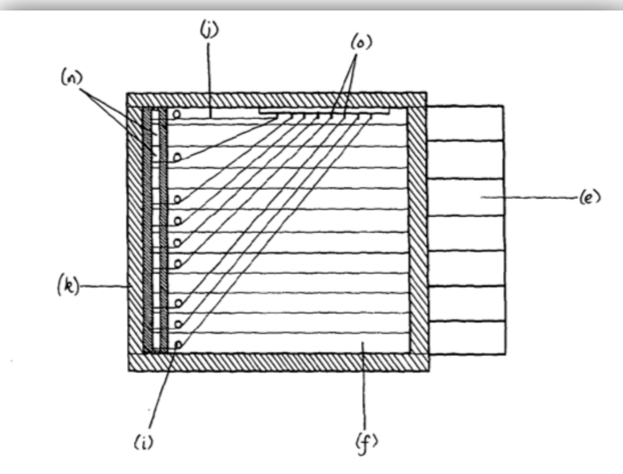
After deliberating on these pressures, I decided to build a skeletal model that could be adjusted with ease at as many points as possible. The tested parameters were:

Key to pivot point = 215 – 220mm

Key drop: range = 7 – 20mm

Far side pivot points: range = 43, 65 and 87mm

Autoharp springs: light and regular (force unknown, but known to be comparable to pressing a key when used as designed in an autoharp) — to prove the principle of reverse damping.



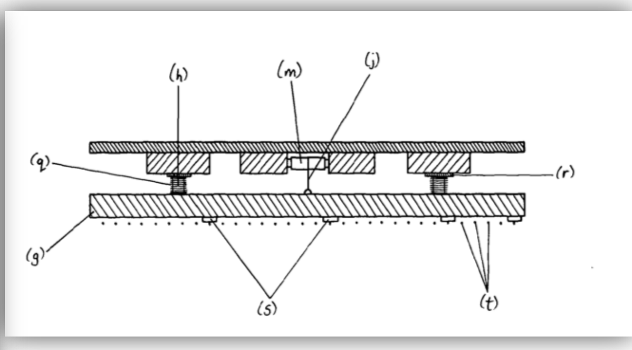


Figure 13. Patent drawings showing the pulley system underneath the keyboard and attached to the damper bar

The Figures above show the rudimentary pulley and string system, which relies heavily on hooks and eyes to provide angle correction rather than pulley wheels. The mechanism was built from the lower action up, establishing first that either set of autoharp springs was indeed sufficient to damp the bars — a key finding.

The results from testing the keyboard and pulley system were initially, more of a puzzle. It turned out that the damper bar springs *were* sufficiently powerful to return the keys, but the force required at the key tip in this configuration was excessive — the keyboard felt very stiff indeed. In addition the key return was sluggish. It was unclear whether or not improvements to the pulley system would improve this. A natural feel to the keyboard being the next priority, I experimented further. The plastic keys of the reclaimed keyboard themselves had sufficient spring to provide key return (a property of the material) providing an independent set of key springs. This increased the range of experimentation that was possible, and I discovered that the most comfortable integration of keys to pulley strings to damper bars was to be found in allowing a certain amount of free key travel before the pulley strings were engaged, with the damper bar clearance set to a very small distance when compared to that of an autoharp. This made immediate sense to me, because it is similar in principle to a piano action, which allows for a certain amount of free key travel before engaging the hammers. The hammer action plays no part in key return on a piano, and in this configuration the damper bar springs similarly cannot return the keys to rest before the coupling is released and the logical consequence is that a set of key springs, which were independent of the damper bar springs (the equivalent of key counterweights), should be integrated on the next prototype, and that this arrangement would provide keyboard feel that best approximated to the range of expectations of a pianist.

In a practical sense this simplified matters from a design standpoint because the two systems could now be considered independently — the damping springs would not have to perform the task of key return, and would be engaged to provide a feel that was akin to engaging the hammer action on a piano keyboard.

As already identified; the pivot point of a piano key is much further back than the playing surface might suggest. This is not immediately apparent because most of this length is hidden behind the casing. Playing keyboards with a shorter pivot point tends to give a pianist the feeling that there is something “wrong” with the keyboard. Pianists commonly (and mistakenly in my opinion) attribute this wholly to the sprung (as opposed to weighted) mechanism. Shorter pivot points result in steeper angle of key drop, and I believe it is actually this aspect that is most disturbing in the feel of cheap keyboards — not the fact that they are sprung. This was a key finding within my own prototype series.

217mm became the settled measurement during the experimentation on prototype one – though at the time I did not completely appreciate its importance. This was subsequently compromised in prototype 2 (because of the dimensions of the salvaged keyboard used, which did indeed have a disturbingly steep angle of drop), and reinstated at prototype 3b, the first bespoke designed keyboard, as the true significance of this measurement in contributing to convincing keyboard feel, was recognized. Future prototype planning (after the current prototype 5) includes separating pivot points for black and white keys.

The stop point for the keyboard was also subject to change; prototype 1 allowed considerable experimentation with the drop of the keyboard and this measurement too has continued to vary throughout the prototype series. Within the experimentation on prototype one I was able to move this easily through a quite a large range, and found that I was attracted to a slightly larger drop than the standard 10mm keyboard drop. After another round of experimentation, and despite some reservations, this was fixed at 12mm within prototype 3b. In the next prototype, I decided to test the possibility that attraction to this deviation from standard keyboard measurements might be attributable to other factors such as the primitive pulley mechanism within the early prototypes. I returned to a 10mm drop for prototype 5, but now, after a significant period of testing, I remain of the opinion that in terms of feel, prototype 3 is the most attractive and responsive and intend to return to experiment on this measurement once more within prototypes 5 and 6.

Pulley System

The drawing below shows a cross section through the mid point of the damper bars. It illustrates the improved pulley system where three separate pulley wheels each turn the

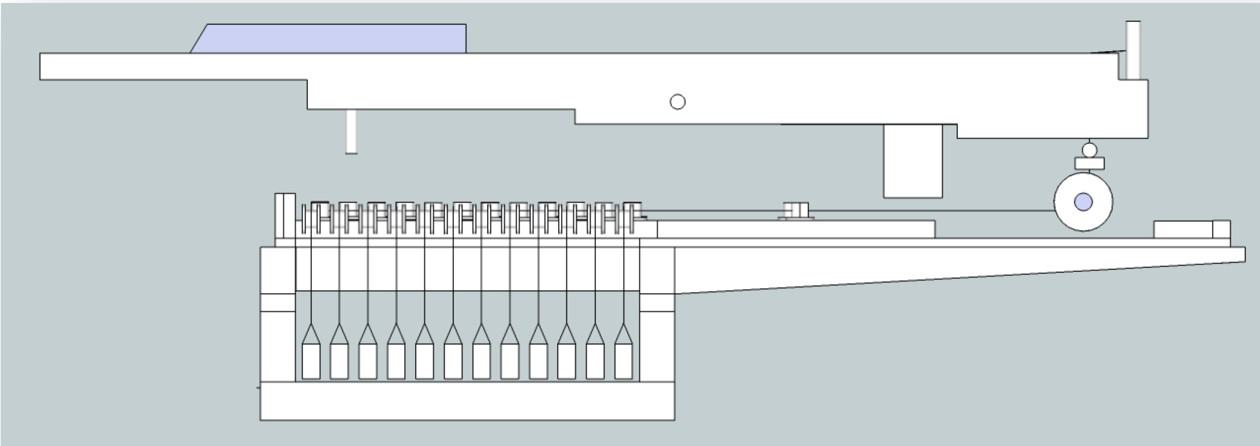


Figure 14. Cross Section through the Keyboard showing the improved Pulley Wheel System

string through an angle of 90°. The following photographs show the pulley wheels realised on prototype 3.

The best material for pulley strings turned out to be waxed linen thread used in Jewellery making and woodwind key coupling. The reliability of the system depends heavily on the

Figure 15. The Matrix Pulley Wheel System of Prototype 2

remarkable properties of this material. It is very strong, and it also has properties of shape forming and memory. It wraps itself to the shape of the pulley system and is not easily dislodged.

The photograph above shows the pulley wheels placed under the keyboard of prototype 2; turning the pulley strings through 90° to the pulley array above the centre point of the damper bars.

This prototype follows the most obvious arrangement, connecting the lowest key to the damper bar closest to the toe end of the harp. This arranges the pulley system such that no string crosses another save for the final top C, which was added to the keyboard at this prototype. This produces the diagonal line of pulley wheels across the matrix that can be seen in the photograph. The remaining top C, whose pulley string can also be seen, crosses all the other strings and is subject to an angle correction in order to allow a final pulley wheel to form a double attachment to the damper bar closest to toe end of the harp.

A key problem that emerged from this was that the harmonic damping was very poor. The problem was so bad that it demanded urgent attention. From previous discussion it was noted that problems with harmonic damping happen because damping occurs at points that are proportional to the speaking string length. If, for example, we find that a damping point occurs at 1/3 the speaking length, then damping might well result in a pitch of $3 \times f_{\text{fundamental}}$ (octave and a fifth) sounding if the string is strummed or caught in inaccurate pinch or pluck when the string is damped.

Harmonic damping is a problem for autoharp and reverse action harps alike. In both it is compounded by the fact that each damper bar damps several strings from the same point and therefore solutions such as the one patented by Walton Page (within his 1915 patented version of the reverse action keyboard autoharp) are not appropriate mitigation strategies — the damper bar cannot simply be moved to a suitable calculated point in relation to a single string. Moreover, the manifestations are so complex and unpredictable as to seem to bear little relation to the simple calculation above — in practice, I quickly gave up calculating and predicting in order to solve this problem; I simply tested and noted results. The problem on autoharp manifests slightly differently, because each string is damped from multiple damping points according to the particular chord bar, two mitigation strategies for autoharp (previously described) are adaptive to the Raph.

The strategy of widening the damping felt to the toe or dead end of the instrument (termed “outrigger”), seemed possible to apply, but was not attractive to me at this time because the remaining strategy (the most extreme strategy for autoharpists), that the damper bar order is changed, seemed to offer greater potential to solve the problem. Autoharpists, as a rule, do not like to change damper bar order, though they are sometimes persuaded to do so in order to mitigate harmonics. The order of the damper bars on a Raph however, is of no consequence to the player – it only matters that the keys are connected to the appropriate damper bar.

Finalising the damper positions within prototype 3 took about six hours over two sessions. There are 12! possible arrangements (479,001,600) but 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. The photograph right is from the treble side. 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:

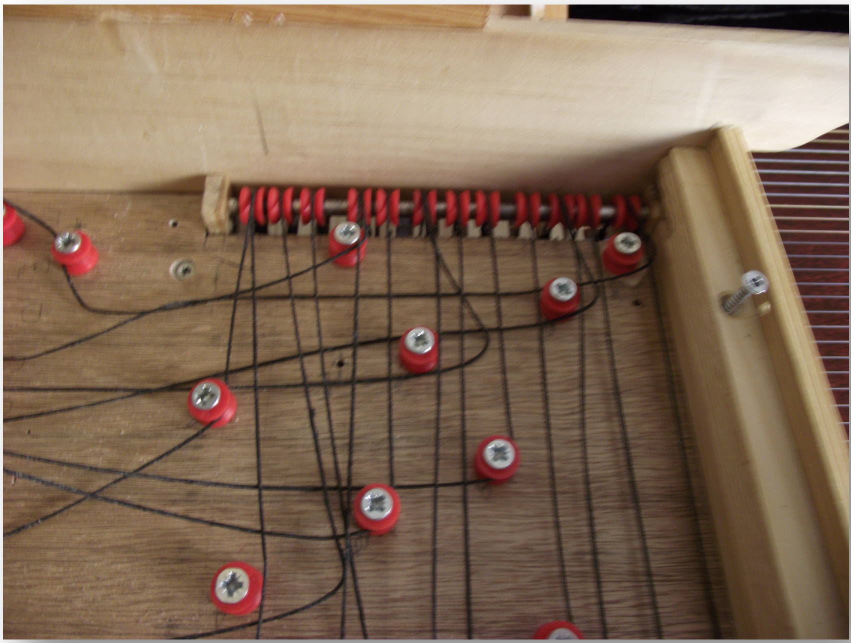


Figure 16. The Matrix & Damper Bar Pulley System

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

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

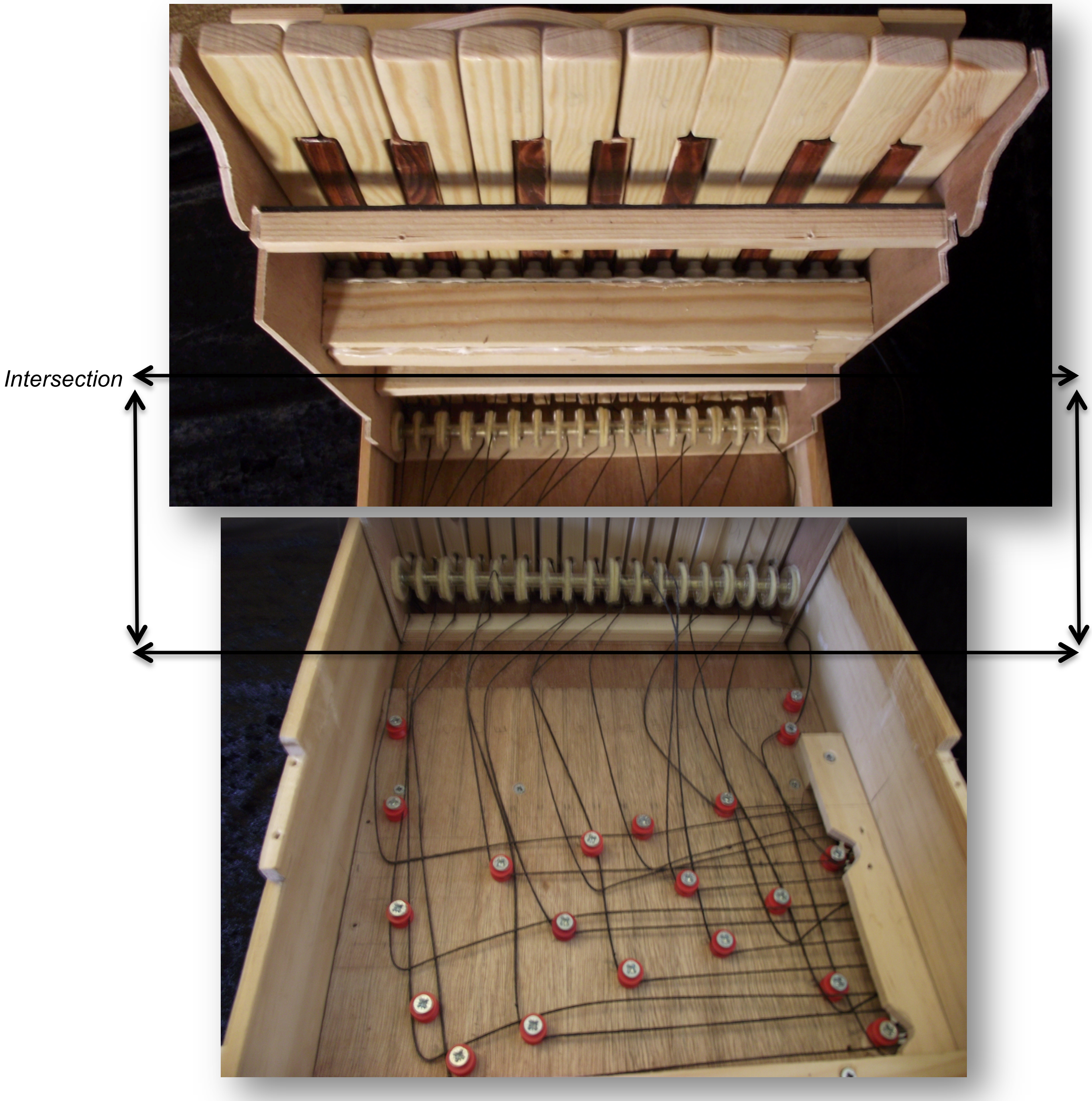


Figure 17. View from the Toe end of Prototype 3

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).

Keyboard Meme-Set Applied to the Autoharp — Problems with the Musical Interface

If harmony only is the aim, then in principle, you only need twelve keys on the keyboard — each acting as a lever system to an octave reverse-damping bar applied to the autoharp body (as described in the introduction) — all chords are possible from this. In practice, as I built successive prototypes I found that the adaptive potential of the interface was significantly improved from pianistic perspective by adding just a few more keys. The first prototype had only twelve, beginning from C at the bottom and ending at B. This arrangement looked superficially pretty because of the symmetry, but I wasn't satisfied with it.

When playing the instrument there is a problem point for the left hand in turning the bottom of the octave into the top whilst the right hand continues up or down. The direction of play for the hands is momentarily separated as if the pianist were caught in a Shepard tone[3]. This is initially disconcerting, and is true for both melodic and harmonic constructions. For example, suppose the right hand on the string surface is playing a rising passage in A minor from A to E — given twelve keys the left hand must drop a major seventh from B to C to continue the run, whilst the right hand continues upwards continuously. We will call this problem "wrap around". If we are to limit the number of keys, this problem will always remain, but can be mitigated, to provide greater flexibility. I knew immediately that I wanted at least a top C on the keyboard, which I added to the second prototype. The doubled keys perform the same functions and are connected to the same damper bar. This spoiled the symmetry of the instrument somewhat, and it still didn't feel quite right.

It is of considerable advantage to be able to change the point at which the left hand drops or rises. But any increase in the number of keys has to be balanced against the conflicting selective pressures of increase in complexity of resulting damping mechanism (and overall

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[3] A Shepard tone, named after Roger Shepard, is a sound consisting of a superposition of sine waves separated by octaves. The amplitudes of the sine waves are controlled by a bell curve, such that (unusually for human perception) the sense of pitch is not given by the fundamental, but by the higher amplitudes at the centre of the bell curve. A typical application developed by Shepard was a series of chromatic tones over the range of an octave where any adjacent tone sounds higher or lower than the previous tone, depending on the context in which it is played. The effect of playing a continuous rising chromatic scale therefore, is that it always rises, but never seems to get significantly higher. This effect is often compared to the visual effects of Escher paintings.

fabrication) and increase in the width of the keyboard. The width of the keyboard was a particular concern, sometime after the construction of the second prototype; I had modified my playing position to that of the photograph shown in the introduction — I play seated, with the harp oriented at a steep angle with the end of the keyboard held between the thighs.

After deliberating on these conflicting pressures, I decided to reclaim the symmetry of the first prototype when I came to build the third, by adding a doubled C to E at the top. This gives a total of seventeen keys, and this seems to be a good compromise. The keyboard is a little wider, but the key sizes have been compromised slightly from the standard range discussed above. Adding five keys made the damping system more complicated, and this is a subject for later analysis. Crucially, this step allows for a variety of points for the left hand to drop or raise the octave. I was also more satisfied with the harmonic range (the increase in the variety of chord inversions and substitution positions approximates more closely to pianistic training for the left hand) it is therefore much more adaptive than squeezing all of the chord positions into one octave.

Understanding Keyboard Evolution

Our interrogation of the keyboard as an interface should include establishing why it is present in the first place. Keyboard instruments have such dominance in Western music and its education system, that without at least some understanding of the evolution of western tuning systems, we accept without question the division of the octave into twelve semi-tones that the interface suggests. But in fact the governing ratio of the twelfth root of two and the strategy of tuning twelve equal semitones that results, are relatively recent innovations, which arise hand-in-hand with keyboard standardization. Our initial exploration of keyboards therefore will lead to a corresponding focus on tuning issues.

Twelve semi-tones appears to be an unusually high number of divisions of the octave when placed in the general context of human musicality, although there are higher — North Indian classical music divides the octave into 22, for example. The most frequent number of divisions is between five and seven, although the number might be as low as 2 (Blackfoot, North American Indian Music) (Patel, 2010, p. 17). The Complex formal tuning systems deployed in North Indian and Western music however, disguise the fact that number of tones likely to be used in any musical presentation is much less than the overall number of tones in the governing tuning system, and that some instruments within the tradition are not even capable of playing all tones in a single performance without retuning; lever harps and to an extent, the orchestral pedal harps are example of this. Keyboard instruments, as they originated (perhaps surprisingly), were also an example of this.

Such instruments exist and thrive within our musical system because a good deal of western music, as it is written and presented to the listener, does conform to the normal range of human musicality; the major scale and common modes all contain 7 pitches, as (arguably) does the minor scale, despite the variation in the 6th and 7th degree (variation is most commonly a contextual either/or decision). North Indian music also conforms more closely to the human norm in performance deployment; individual *ragas* commonly use between five and seven divisions. These performance sets also conform to another norm across human musicality — they are asymmetrical. The range of between 5 and 7 pitches, in conjunction with the asymmetry, is optimised to human pattern matching capability with respect to pitch — the differences in the asymmetry across cultures account for a great deal of the culturally specific meaning which is conveyed within musical performance and composition (Patel, 2010, p. 314). The differentiation by asymmetry is not localized to pitch systems; it is also present within tonal languages and arguably informs all human ability to classify (Saffran, Hauser, Seibel, Kapfhamer, Tsao, & Cushman, 2008).

An unusual feature of a good deal of Western music however, is its propensity to change key within a piece of music (modulation). This is a process that has become increasingly common through several centuries of musical change; each generation of composers and performers gradually expanding the boundaries of key change, and the range of complexity within individual chords. We might usefully describe key change, as a realignment of the tonal centre for some duration within the piece, such that an alternative set of pitch relationships is now the subject of elaboration. The equal temperament division clearly allows for modulatory procedure, because all intervals except the octave are slightly compromised with respect to Pythagorean whole number ratios based on the harmonic series, but the ideal tuning response to modulation would be a set of divisions based on simple whole number ratios originating from the new tonality. Analogue instruments without frets, such as violins, have the capacity to achieve this accuracy of tuning (though in practice this is highly dependent on the skill of the player) but for highly digitised instruments such as keyboards this is not possible.

This was the problem that faced early makers of keyboard instruments; if we take an octave of keys on a keyboard, and tune simple ratios[4] for a given key centre — then the keyboard will play perfectly in tune for that key. The tuning will also be adequate for related keys, but will sound increasingly out of tune as function of distance from the key centre used for the tuning origin. There is thus a conflict presented to the player, composer and instrument designer. The linearity presented in the keyboard interface suggests that the capacity to modulate freely to all keys is relatively easy to achieve, but tuning simple, whole number ratios does not allow this possibility.

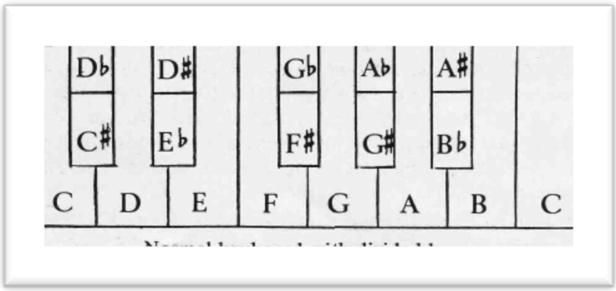

Figure 18 Common keyboard arrangement to allow alternative tunings; divided black keys, (Thomas, 1975). Permission Sought

There are three possible solutions, all of which arise in keyboard evolution:

1. Complicate the keyboard interface to allow for greater tuning possibility. A common arrangement is illustrated in the diagram above.

In this arrangement the black keys are divided into two and each connected to a separate sound producer (string), tuned slightly differently.

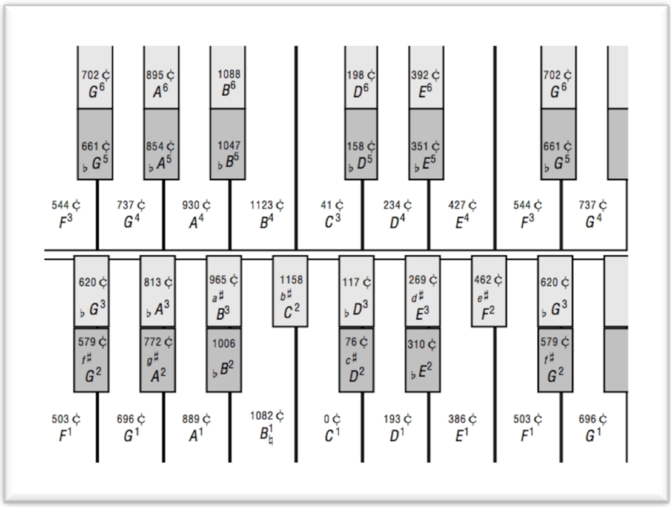

Figure 19. The 31 note cycle applied to Vincentino's harpsichord (Lunlunta99, 2007).

Status: Public Domain

The height of complexity for this approach is embodied in the 31 note cycle used by Nicola Vincentino (1511–1572) who describes a harpsichord with six rows of keys (Thomas, 1975, p. 150).

The diagram right shows the tuning system (in cents) as applied to the 6 tiers of keys. There are key points to note here: firstly, despite the complexity, the fifth remains a compromised interval throughout

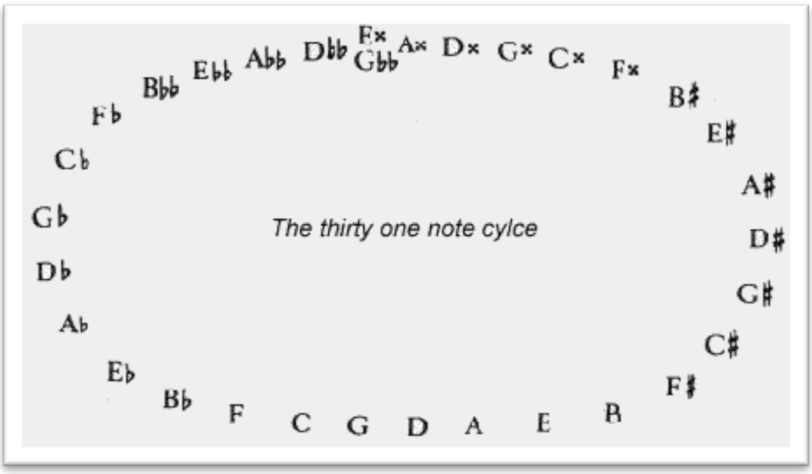

Figure 20. The 31 note cycle perhaps for 2/7 comma tunings (non – cycling) (Thomas, 1975). Permission sought

the enlarged circle of fifths though it is very close indeed to a simple 3:2 ratio. Secondly, the number of individual stable tunings of strings that need to be achieved and maintained is very large. Lastly and perhaps most significantly, the keyboard interface is very complicated indeed — difficult for the player to interpret, and combinations physically difficult for the player to achieve. The photograph below, an extant harpsichord made by Vito Trasuntino Venice dating from around the same time, with five rows of keys, shows how this complexity actually appears to the player.

Figure 21. Trasuntino's archicembalo (Museo internazionale e biblioteca della musica di Bologna, 2011)

Status: Free Art Licence

2. Another possibility explored by early keyboard makers was to couple the key to alternatively tuned strings. The technology necessary for this was already extant: developed for timbral and dynamic variation, an even more pressing problem than tuning for harpsichord makers. Unlike the keyboard of a piano, harpsichord keyboards are not responsive to key pressure, and dynamic and timbral contrast is affected through terraced introduction of alternative couplings. Accessed through a mechanism at the keyboard; strings plucked closer to bridging points can for example, provide a brighter tone, or a second set of strings tuned at the octave can be coupled in. Utilizing this mechanism for tuning alternative is attractive from a performance perspective because an instrument can be set up at the outset of a musical presentation or modified during a pause, but the keyboard interface rendered to the player during performance is always the same twelve semitones.

3. The third possibility is that the tuning system itself be compromised to match the capability suggested by the linear keyboard interface, and this is in fact largely what has happened within western music. We do not normally encounter divided keys on contemporary keyboard interfaces, nor do we encounter alternative coupling. We also do not normally encounter any of the alternative cycling temperaments that compromise

(temper) simple tuning ratios unequally across the 12 semitones. The tuning system which has emerged as standard is equal temperament. It is the blandest possibility, but also offers the most obvious potential for compatibility in different musical situations, and was therefore the most obvious candidate for standardisation for instrument manufacturers.

These historical approaches to increasing the tuning flexibility that a keyboard instrument provides, whilst fascinating to consider, are not advantageous in design terms for the Raph; but tuning flexibility *is* nonetheless well worth considering. Although we expect keyboard and equal temperament to go hand-in-hand, it is only by convention. We encountered diatonically tuned autoharps in the first chapter and equal temperament is clearly not the only, or even the most advantageous tuning choice for this arrangement. If extreme modulation is not necessary and access to diatonic range is prioritised then alternative simple ratio tunings are likely to be preferable.

To what extent is retuning for particular performance possibility a realistic proposition on an autoharp/Raph? Guitars with 6 (or the doubled 12 string variation) are often tuned alternatively with reference to a particular key centre; for example, an open G tuning will retune the strings to simple ratios to formulate a beatless G chord using the open strings (tuning DGDGBD). Tuning only 6 (or even 12 strings) for a particular performance situation is a perfectly reasonable proposition. Tuning 36 strings (standard chromatic autoharp specification) is rather more ambitious; with practice, I have found the time taken to accomplish a full tuning to be between 12 and 20 minutes with the current design arrangements. This is a significant interval of time, but not unreasonable when compared to the 230 strings of a piano.

However, there is possibility for considerable enhancement here from a design perspective. Autoharps traditionally rely on friction pins, similar to (though smaller than) those on a piano. Higher end models include a fine-tuning arrangement at the dead pin end. Zither pins, which require a hammer for tuning, are ungainly, imprecise, slow and prone to error, but they have the advantage of being cheap, and fitting easily into a small space that the large string array allows. The fine-tuning mechanism at the dead end of the instrument is ill-suited to the Raph configuration (as opposed to the autoharp) because so much of the dead end of the instrument is covered by the keyboard, making access difficult. In terms of the engineering of tuning mechanisms there are certainly better alternatives. Guitars need no fine tuners because the precise movement of geared machine heads renders this unnecessary: precise tuning is achieved with relative ease and stability through one mechanism. A discussion of possible implementation of this device to the Raph is given at the end of this chapter.

Later keyboard innovators had no such concerns with the complexities of tuning, and there are a number of 12 semi-tone alternatives to the standard keyboard that offer direct alternatives to the traditional piano keyboard layout that we should consider.

Keyboard Alternatives

An alternative to the traditional keyboard array was proposed and patented in 1882 by mathematician and musician Paul von Janko.

Figure 22. Paul von Janko (Doge, 1911, p. 90)

Status: Public Domain

The keyboard layout is shown in the plate below. We may first observe that there is no intention to reference the keyboard from any particular point, as is implied in the layout of a traditional keyboard, because the layout is symmetrical. Each row sets out a whole tone scale, the corresponding row below or above is a whole tone scale, one semitone displaced. The pattern of colouring white – natural, and black – sharp/flat is retained from the traditional keyboard layout, which provides visual clues to translate note meaning.

The design intent of this symmetry is that it leads to a reduced learning time because scales, modes and chords are to be found in similar positions throughout the keyboard.

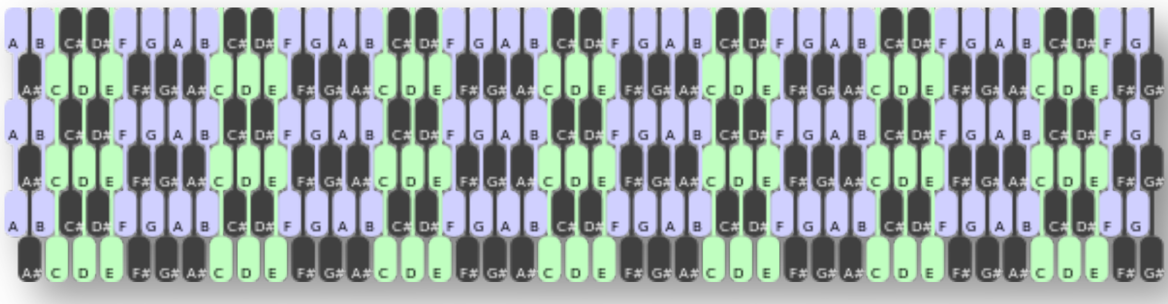

Figure 23. The Janko Keyboard Layout (Handige, 2008) *Status: Public Domain*

Consider a major scale in this arrangement — three whole tones along a row, then a row change to accommodate the semitone between E

Figure 24.The Janko Piano (Museum of Musical Instruments Germany, 2010) *Status: Creative Commons*

and F, followed by four whole tones, and lastly a second row change.

Unlike a traditional keyboard this pattern produces a major scale irrespective of the starting note. The learning times of traditional building blocks of technique, scales and chords, are therefore said to be reduced when compared to a traditional keyboard layout. Further, as a direct consequence of the symmetry, transposition (a difficult skill on a traditional keyboard layout, becomes trivial). These properties define the Janko layout as Isopmorphic; self-transposing and symmetrical, such that the same sequence is always accessed by the same shape. Fret boards may also be said to be isomorphic in all but the proportional spacing within the frets and there are similarities to the learning approaches required for isomorphic keyboards and fretted string instruments.

Secondary aspects of the design intent are to reduce the nominal size of the keys to increase stretch potential, and to increase the potential for the hands to interact independently in the same range; this is the purpose of the multiple layers.

A good demonstration of the keyboard in action is given by the musician Paul VanderVoort (VanderVoort, 2012). The video extract presented in this link was recorded in 1986, Vandervoort appears to have become interested in this keyboard design quite early in his career. However, this attraction is highly unusual for a pianist and the proportion of users of the Janko (or any other isomorphic) array on large keyboard instruments, such as pianos, organs or harpsichords, is negligible, and has not reached even the minority user levels of, for example, Dvorak typing keyboard layouts. Janko himself spent his final years in exile in Turkey; allegedly fleeing the debts accrued through investing in his invention.

Explanations for the lack of traction within the musical community highlight the immediately obvious features of lock-in, beginning with the earliest commentators. Alfred Doge (*Pianos and Their Makers*), for example, writes in 1911 “The piano virtuoso and teachers of the present day are opposing the Janko keyboard because its universal adoption would mean for them to forget the old and learn the new. The music publishers object to it, because their stock on hand would depreciate in value, as the Janko keyboard naturally requires different fingering than that now printed with published compositions” (Doge, 1911, p. 80).

Explanations feature; continuity and compatibility with regard to manufacture, maintenance and expert performance, and pedagogy, as reasons for lack of acceptance; they do not tend to challenge the advantages claimed by the design itself, and they do not seek comparative analysis as to why the range of variation is so narrow within piano design, when compared to, for example accordions.

The case for real and decisive learning or technical advantage remains to be proven for the Janko and the entire story, and resulting debate, has many parallels with the QWERTY/DSK debate. Since information is given by investing in interfaces to a level of expert performance, the debate tends naturally towards polarised positions; evidence is difficult to assess and truly objective evidence is very difficult to gather.

However, there is no technical design obstacle to producing a Raph that incorporates a Janko, rather than a standard piano keyboard; compatibility is established from the original design parameters set by Janko (that it works with the standard string layout of a piano). Nor should we dismiss the potential to attract early adopters to this interface, because the interface might prove attractive to players of free reed instruments such as the accordion (where isomorphic interfaces dominate) or even to players accustomed to fret boards.

Free Reed Interfaces — Comparing Range of Variation

Free reed instruments display an astonishing variety of playing interfaces, including a large variety of traditional and alternative keyboard layouts (accordions) which include isomorphic layouts; there are also finger holes and keyed mechanisms similar to woodwind key extensions (*shen*) and direct-access, un-damped arrays (harmonicas). This stands in sharp contrast to pianos, organs and harpsichords, where the playing interface has evolved towards a stable simplicity, and is highly resistant to modification.

Why should this be? Firstly, in evolutionary terms we pre-suppose that we are discussing similar units of classification; a moment's consideration tells us that we are not. Pianos, harpsichords, organs (we might add to this all similar MIDI keyboard interfaces) are natural units of classification from a playing (and design *for* playing) perspective. We draw a lineage through them precisely for this reason, but the sound producers are variable; plucked strings, struck strings, reeds, air reeds and once into the electronic domain; synthesis and sampling. Free reed, is a classification *by* sound producer; a very different perspective.

According to the most used classification system (Hornbostel-Sachs) free reed instruments are classified at 412.132. (Aerophones/free aerophones/Interruptive free aerophones/sets of reeds/*accordion, harmonica (sheng) etc.*) — fourth level classification. Pianos, organs and harpsichords classifications are dispersed, as you would expect because the sound producers can be different, and the secondary interface is the unifying factor. There is however, no reason not to draw a unit of classification by keyboard interface, if it is useful, and as long as we remember that we are comparing different units of classification.

A better like for like comparison would be to compare the entire spectrum of string arrays, together with their playing interfaces, to the entire spectrum of free reed instruments and the variety of interfaces that they display — and here we find a comparable level of variation. The comparison seems reasonable because we are now classifying and comparing two types of sound producers and their deployment, and, because the comparison illuminates crucial differences between the two, it enables us to understand exactly why free reed keyboards have evolved differently.[5]

Assuming that we accept (for the moment) that based on the empirical observations above, the comparison between free reed and string arrays is a valid categorical comparison: what differences can be observed in the two spectrums?

Firstly, change of pitch is conveniently addressed in design terms through stopping the same strings at different lengths (*erhu*, violin, guitar). Variable combinations of polyphony are achieved through a mixture of stopping and combining strings in limited numbers — limited to two-at-once and occasionally three on the violin, but

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[5] We might also note that within the same Hornbostel-Sachs classification systems, string instruments are a top level classification (chordophones: *sound is produced by the vibration of a string across fixed point*), so according to the most used system we are *not* comparing like for like. Hornbostel-Sachs however, is one of many proposals for a classification system of musical instruments, and in its most traditional form, displays many such inconsistencies.

with the addition of frets (which may be viewed as a limited secondary interface) increasing to 6 string combinations on the guitar. Digitised arrays with secondary damping interfaces, as we know, range from the medium sized autoharp/Raph (36–49 strings) to the extreme piano (230 strings). Such arrays are extremely resource intensive.

In contrast to a string, an individual free reed has a very limited capacity for pitch change; each is a single unit, tuned to a fixed pitch. The (more or less) fixed pitch nature of the free reed means that unlike string arrays we do not expect instruments featuring smaller numbers of reeds. On the other hand, individual reeds are also cheap to produce and highly flexible in terms of design deployment, when compared to strings. They are not under tension, and instruments are free from the design constraints imposed by this. They are also small and require minimal space and thus lend themselves to incorporation in medium, large and very large arrays. Free reed instruments are, therefore, always formulated in arrays, but when compared to a comparable string array, they do not appear to be large instruments.

Figure 26. The Sheng (Seasonaldemand, 2012)

Status; Creative Commons

Arrays, with no secondary damping mechanism are present within the spectrum of variation, but are significantly outnumbered by the number of instruments that do incorporate secondary damping mechanisms.

Free reed instruments are thought to have propagated to the west from China. Direct evidence of Chinese instruments dates as far back as 1100 BC, and an even earlier Malaysian instrument might have been the origin within China. Evidence for the existence

Figure: 25. Guo Yi (郭艺, Pinyin: Guō Yì), a Sheng player beside the River Thames, outside the Tate Modern Gallery, London, England. (Pingstone, 2005) *Status: Public Domain* of free reed instruments is also found in ancient Greek and Egyptian civilisations, which may be independent points of origin.

The Chinese sheng has an intriguing secondary damping interface not used in the west, giving the instrument good potential for polyphony, and for melodic/harmonic combination playing, the instrument also looks very impressive.

It is commonly used to accompany soloists, and within ensembles, plays both a harmonic and melodic role. The design consists of up to 21 pipes coupled individually to doubled free reeds tuned to the same resonant frequency (Doktorski, 2000). The second set of reeds are reverse in orientation to the air stream so that the instrument responds similarly to outward and inward breath. Each pipe has a finger hole drilled within its bore, which changes the resonant frequency of the pipe. The pipe will thus only sound when the finger hole is covered, making it the same resonant frequency as the reeds. Pipes can be sounded individually or in varying combinations (Sheng_(instrument), 2011).

Figure 27. The modern Keyed Sheng (Taobao (Searching for Treasure, 2012))

Permission Sought

This highly flexible interface has been developed through the second half of the twentieth century with the addition of lever-keyed holes, providing independence between the pipe arrangement and hand access to keys. The number of pipes within the instrument has risen to 36, with a full chromatic range (Sheng_(instrument), 2011). A good demonstration of the varied capability of the instrument was given at the Atlas Academy, Amsterdam in 2009, by the player Wu Wei (Wei, 2009).

Harmonicas — Comparison to String Instruments Designed for Melody

Harmonicas are examples of the less numerous, un-damped free reed arrays, which rely on reed alignment within the array for access to advantageous combinations of notes. The most common reed arrangement (below) is accredited to Richter.

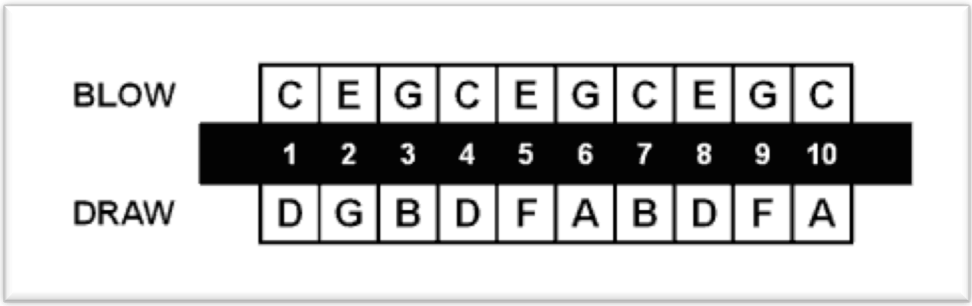

Figure 28. The Original Richter Tuning (Bennet-Lovsey, 2012)

Status: Permission granted

The earliest published reference to this invention is to be found in *Zeitschrift für Instrumentenbau* (Journal of Instrument Making) Vol. 3, No. 21, published in April 1883 (Missin, 2008). According to harmonica history, Richter is credited with the invention of blow/draw reeds and the pitch arrangement depicted above. As we have seen, blow/draw reeds were in existence long before this point; but the original application to this particular lineage of free reed instruments is probable. The same is in fact true for the reed arrangement, which was common in other European bisonoric[6] free reed instruments of the time, including the accordion (Missin, 2008).

The harmonic possibility offered by this array is apparent immediately from the arrangement; as are its severe limitations. The chromatic variant provides a full chromatic range by means of a slider, which engages a second set of similarly

Figure 29. Chromatic Harmonica (slider right) (Arent, Chromatic Harmonica, 2005; Arent, Accordion, 2006)

Status: Creative Commons

6 Bisonoric instruments utlise blow and draw reeds of different pitch

tuned relationships, a semi-tone higher. This enriches the melodic capacity of the instrument, but its harmonic capability remains limited.

In fact, despite the name “harmonica” — the design intent of both instruments is primarily melodic, the chromatic harmonica, most commonly used as a solo instrument in jazz ensemble settings, and the diatonic harmonica as a solo instrument for blues (for blues, the layout above depicted as C would be most commonly deployed for blues played in G).

The first great strength of the arrangement of the instrument is its timbral capacity. The mouth is placed directly behind the reed, and this enables a direct coupling of the mouth (cavity) to the instrument. Altering the shape of the mouth when playing therefore alters the timbre of a note, or combination of notes, to an extent that is unusual within western music. Good demonstrations of the instrument involve descriptions of jaw and tongue movement, and describe shaping of the mouth cavity in ways similar to language. This direct access also enhances the ability of the player to choke the air flow to the reeds to perform analogue pitch bends, adding to the language-like character of the instrument. Access to single notes can be facilitated by damping adjacent reeds with the tongue to enable a single note or melodic strain. A second strength of the instrument, particularly utilised in blues harmonic playing, is its rhythmic capability, facilitated by the learning of suitable vocables. Again, there is a striking speech-like quality to the resulting music, distinguished by accent and timbral variation.

										D		←	**Whole step blow bend**
								F	Ab	Db		←	**Half step blow bend**
	D	F#	A	D	F#	A	D	F#	A	D		←	**BLOW**
D	1	2	3	4	5	6	7	8	9	10			
	E	A	Db	E	G	B	Db	E	G	B		←	**DRAW**
	Eb	Ab	C	Eb		Bb						←	**Half step draw bend**
		G	B									←	**Whole step draw bend**
			Bb									←	**Step and a half draw bend**

Figure 30. Diagram to show blues scale in A played on a D harmonica in second position (Bennet-Lovsey, 2012) status: Permission Granted

We can draw a number of comparison points with the string arrays without secondary damping mechanisms previously discussed; violin, *erhu* and guitar — the properties display some convergence. Violin and harmonica display great capacity for timbral variation; the speech-like qualities of the harmonica are very different to the bow of a violin, but the capacity for variation is comparable. There can be no equivalent to the analogue pitch variation of the un-fretted violin within free reed designs, but the harmonica does, like the guitar, display capacity to bend pitch. The capacity to achieve polyphony is present in all harmonicas, but like the violin, is limited. Lastly, though the range of genre engagement is very different, the roles these melodic instruments perform within their respective ensembles have many commonalities.

A significant divergence however is the relative size of the instruments; for reasons already observed free reed arrays require a much greater number of individual sound producers, but despite this, the instruments are relatively small in size. A 16 hole chromatic harmonica has a four-octave range, and to increase this further would not significantly alter the size of the instrument at all. This is a significant difference, which continues through the spectrum of design of free reed instruments.

Even very large arrays of free reeds, comparable in range and possibility to piano or church (pipe) organ remain portable. Considered from a player's perspective, this means that a portable instrument interface can become highly esoteric; adapted to an individual player because the instrument always travels with the player and can be relied upon not to change. Coupled with this, free reed arrays are very easy to re-deploy to the requirements of different interfaces, and unlike the majority of piano manufacturers, makers of high quality free reed arrays are highly responsive to even individual specifications.

In contrast, a pianist, organist or harpsichord player is required to play on the instrument provided at location, often in high pressure situations and without any testing or adjustment time allowed at all. This presents a significant challenge, and the player is reliant on good standardisation. There is therefore, a constant selective pressure to achieve and maintain standardisation across large, none portable keyboard instruments, particularly pianos. This is slightly different to the standard features of a technological lock-in situation, which are often cited as reasons for keyboard resistance to change. It is also *not* a conspiracy of continuity on the part of the establishment, and is *not* related to conservatism of manufacture, which are other factors commonly cited; it is simply a different selective pressure.

Accordions and concertinas, commonly classified together in colloquial terms as “squeeze box” rely on a bellows mechanism to sound the free reed arrays, which is held between the two hands and alternately squeezed and drawn apart. This group of instruments is reliant on a secondary damping interface in all cases, is always portable, and the interface variation is very large.

There are commonalities, and we should begin with these: located on the right hand side of the bellows is an interface designed for melody accessed by the right hand — it is quite common for this to be a reduced size standard keyboard arrangement. The left hand accesses an interface designed for accompaniment (from the left side). The two interfaces are entirely independent, and in the vast majority of cases the playing interfaces are different for each hand. There are references to left-handed instruments, but these appear to be very rare.

The photograph plate below shows seven examples chosen to depict the variety, and to enable us to understand and classify the diversity, in order to draw conclusions as to applicability to the Raph.

Figure 31. Seven examples of Free Reed interfaces, chosen to depict variety
Top left: Hohner Club II (Woehr J. , Jax RFCB Button Accordion Page, 2009) Status: Permission granted
Top middle: Weltmeister Piano Accordion (Arent, Accordion, 2006) Status: Creative Commons
Top Right: Reuther Uniform Keyboard System (Woehr J. , Jax RFCB Button Accordion Page, 2009) Status: Permission sought
Middle left: Bandonion: (Woehr J. , Jax RFCB Button Accordion Page, 2009) Status: Permission Granted
Middle middle: Mythos No. 27 (Murray, 2009) Status Permission granted
Middle right: Russian bayan (A World of Accordions Museum in Superior, Wisconsin, USA, 2008) Status: Creative Commons
Lower left: Hayden Duet (Woehr J. , Jax RFCB Button Accordion Page, 2009) Status: Permission sought

Top left is a Hohner Club II; this is a bisonoric system similar in capability to the harmonica. There are a great many variations of diatonic instruments and the most significant variation pressures at this level are genre and region. Woehr reports that “there is probably at least one variation for each European ethnic group” (Woehr J. , Jax RFCB Button Accordion Page, 2009)

To the right of this is the Weltmeister piano accordion, the right hand plays the two octave reduced-size standard keyboard, whilst the left hand accompanies. The *stradella* style accompaniment system, at its most flexible, will provide a mixture of chords, with up-to-two rows of single bass notes. A single column from this array will sound; isolated root, the third pitch of the major chord, then, proceeding from the third button; major, minor, dominant 7^{th} and diminished 7^{th} chords. The next column will repeat this pattern at an interval of a fifth. There is variation in chord deployment and the circle of fifth patterning, but the underlying principles can be understood from this description. The instrument is therefore chromatic, but with limited chord choice. In many ways, although the chord choice is wider, this type of instrument exhibits similar limitations to the autoharp, because the harmonic choice is locked-in to standard sets.

The (right hand) piano keyboard (intended for melody) is clearly fully chromatic. This instrument is most usually the image that comes to mind in considering an accordion within the UK, we tend to picture the instrument as a keyboard on one side and a row of buttons on the other. This popular image might lead one to suppose that the chromatic piano keyboard is the most favoured melodic interface. A reading of literature by designers, makers and players of accordions, however, reveals that the opposite is in fact the case; that on balance the traditional keyboard is not considered the most advantageous chromatic interface. There is considerable regional variation; Hans Palm reports that only 10% of Scandinavian accordions incorporate a piano keyboard, whilst in America the figure is 90% (Palm, 2006).

Top right is a similar instrument to the piano accordion, but the melody interface is clearly a Janko keyboard. Brian Hayden attributes the invention of the Janko layout to a much earlier 1811 patent by Trotter, though no known instruments resulted from this patent. He cites Janko as a *re-inventor* in 1885 and reports its incorporation in the accordion early in the twentieth century under the name uniform system (Woehr J. , 2009). This keyboard layout is rare on the accordion. Isomorphic symmetry on the accordion is more commonly created using interlocking rows of minor thirds rather than the whole tone of the Janko keyboard. In the example below, which is common, the rows of minor thirds are transposed by a semitone.

The bandoneon (middle left), the Russian bayan (middle right) and the high end Mythos free bass accordion (middle) all use variations of this system. The left hand manuals of many free bass accordions can be switched to the Stradella chord system described earlier. Good players of the free bass system report that piano and organ music can be read on the instrument with no adaptation. Again, the relative size of the instrument is striking, for whilst these are bigger and heavier than some of the smaller accordions, they certainly maintain portability.

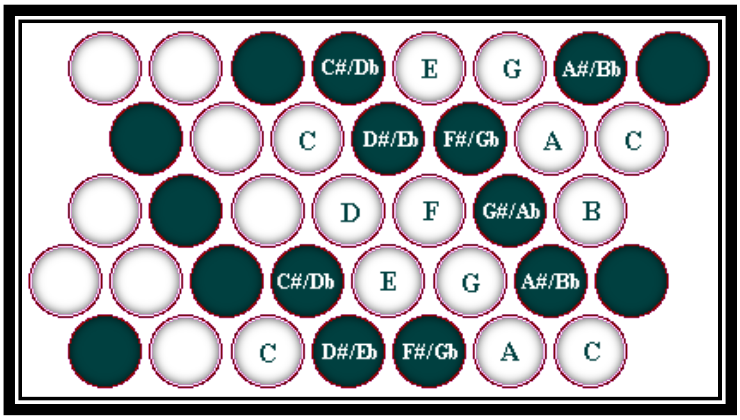

Figure 32. Isomorphic Keyboard Layout (Swedish System) based on minor 3rd symmetry (Palm, 2006)

Status: Permission Granted

The lower left concertina is a Wicki-Hayden layout (for both hands). This is a chromatic layout using whole tone steps (like Janko) but with the alternate row displaced by a fourth rather than a semitone. Wicki-Hayden is named after two independent inventors, separated by a century. Kaspar Wicki originally patented this layout in 1896 — again inspired by the Janko layout (Woehr J. , Hayden Duet, 2009).

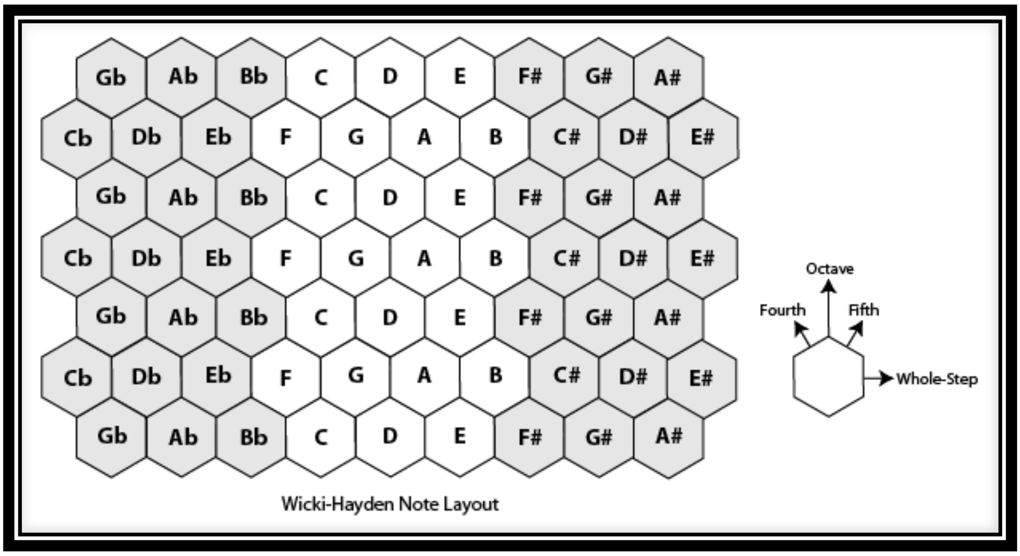

Figure 33. Diagram of the Wicki-Hayden note layout used on some button accordions and some isomorphic button-field MIDI instruments. (Waltztime, 2010)

Status: Creative Commons

Facts which become apparent from investigating accordion keyboard layouts, are that isomorphic arrangements are generally held to be superior; the claims for greater flexibility and reduced learning time are accepted. It is also accepted that different interfaces are required for different musical tasks, and that there *should be* variety. Piano accordions are held to be suitable for pianistic adaptation, but are not thought to be the most flexible interface.

The Raph, like the accordion, is portable, and the autoharp already displays variation consistent with a lack of selective pressure on standardisation (similar in level of variety to the accordion). So we might expect that a Janko, or other isomorphic keyboard adapted Raph, could be a viable and attractive variation.

There are some factors which need careful consideration in assessing their suitability as alternative keyboards for the Raph. Although perhaps not immediately apparent, all of the isomorphic layouts discussed are dependent on hexagonal tessellation, and share properties of self-transposition. However, they do differ from each other in several respects. Both the Wicki-Hayden layout, and all of the layouts basing the isomorphic symmetry on a minor third, introduce vertical movement to neighbouring pitches. This is not present in either the standard or Janko keyboard arrangements. To clarify: pitch movement is accomplished not only through movement along the rows (with incidental changes in manuals) it also moves up and down columns of hexagonal tessellation. The Wicki-Hayden layout develops this concept fully. It is illustrated by the hexagonal icon on the right of the Wicki-Hayden diagram, which denotes the vector of interval travel (vertical and horizontal). Note that direction of travel for semi-tone movement is missing; and is problematic in this interface. The repetition of the first manual is an octave transposition — not a straight repetition like a Janko layout. Movement by octave is executed vertically rather than by moving along the row. To play a major scale in this layout, consider the white hexagons patterned in alternate rows of 3 and 4. The final octave pitch is given by moving up to a third row, this is a very easy repeating pattern.

Minor scales however present more of a challenge. Minor third based layouts need not pursue this vertical movement to the same extent. However, even for simplest case, three distinct rows of minor thirds are needed in order to provide access to all 12 semi-tones rather than the two rows of standard or Janko layouts, the five layer keyboard (figure 3.22), allows movement of five semi-tones in a vertical column, and so similarly introduces vector, as opposed to scalar, interface navigation.

This combination of vertical and horizontal movement is highly suited to the “squeeze box” arrangement because both arms perform double duty on all these instruments; simultaneously maintaining even pressure on the bellows and providing a support platform for hand access to the keyboard. In all, the wrist can be angled easily, but weighted lateral movement from the arm using the thumb as a pivot (the lynchpin of traditional keyboard technique) is difficult.

The combination would be less suited to the Raph for three reasons. Firstly, the hand orientation on the Raph is designed to be comfortable for a pianist, and to allow full integration of the thumb as a pivot. The keyboard is addressed from a supported position, with a straight, free wrist; as a result, weighted arm movement across the keyboard is not hindered. Too much vertical movement could disturb the carefully achieved balance between the hand positions. Secondly, there are considerable technical design obstacles to the repeating patterns presented in some of the keyboard layouts presented above, in achieving a successful coupling to the Raph damping mechanism. Lastly, although accordion keyboards (like the

Raph keyboard) are passive (they do not produce a sound by themselves), the relationship to the sound producers is different. The accordion player has secondary interfaces under *both* hands, and these act in conjunction with the bellows, whose action is often likened to a bow — the shape and orientation of the reeds (and how they are addressed) is not a technical issue for the player. In contrast, the Raph or autoharp player has a secondary interface available to only one hand, which is coupled to a linear chromatic string array — changing the string array to match these interfaces is difficult to imagine, and presents significant technical obstacles.

The piano keyboard provides an intuitive reflection of the linear pitch layout. The Janko layout would provide a similar intuitive reflection, but the non-linear layouts would not; the isomorphic symmetry achieved through a minor third, and the displacement of a fourth integral to the Wicki-Hayden layout would sit uneasily alongside the linear string layout, and the activity of the right hand in contact with the strings.

I am confident in the logic of this particular part of the conclusion, and put forward the traditional keyboard and the Janko layout, as a suitable isomorphic alternative, for implementation on the Raph. Assessing the advantage of one over the other is more difficult, and is complicated by the issue of wrap-around when applied to the Raph. The most significant claimed advantages of an isomorphic layout seem to be the ease of structure learning and transposition. To what extent would these advantages be preserved in the reduced keyboard arrangement of the Raph — with the complication of wrap-around? As a first step I would suggest raising the compass to an octave and a fifth. This would not place pressure on the most significant measurement, which is the keyboard width, because the width of individual Janko keys is less than for a traditional keyboard. This extension would allow a root position placement for every triad (but the full benefit for example for four note substitutions would not be afforded without an extension to two octaves), and keyboard width would not allow this within the current design constraints. Melody is similarly constrained by the issue of wrap-around. In order to play a two-octave major scale on the string surface, it is necessary to repeat the same octave pattern on the keyboard (this is well worth practicing because it mirrors many melodic situations). It is, admittedly, quite difficult to repeat some of these scale patterns on the traditional keyboard. A preliminary assessment leads to the conclusion that this probably would be easier on the Janko keyboard. Clearly the self transposition benefit would be lost for scales above G but the patterns do seem to retain a repetitive quality when compared to the esoteric intricacies of the traditional keyboard.

However, this is extremely difficult for me to compare because the principle claimed advantages (self-transposition and structure learning) appear trivial to me. I compare from a situation of complete familiarity with traditional keyboard to non-familiarity with Janko. It is difficult for me to remember a time when I was not completely familiar with all scales and chords on the traditional keyboard, I am, therefore, continuously transposing familiar patterns into unfamiliar, on the supposedly easier interface.

Further, objectively I consider that much more evidence is needed to support the claims for a reduced learning time for isomorphic keyboards, and treat the claims for this extremely cautiously. Claimants fall into two categories, and neither provides a good evidential platform. They may be proceeding from a situation of a secure knowledge of traditional keyboard — in which case you would expect a reduced learning time, or they proceed from a situation of frustration and incomplete learning of a traditional keyboard — in which case, you would, again, expect a reduced learning time.

Nor do I accept that a reduced learning time, should it be proven, necessarily leads to a more secure or superior technique as a final outcome; and for reasons previously stated, would predict that in fact the opposite might be more likely — that asymmetry, a fundamental factor in human pattern matching within music, results in increased technical security.

However, designers must be pragmatic; and I do accept that there is a strong belief in the technical advantages of isomorphic keyboards within the accordion community, that they are successfully deployed upon this instrument, and that this community allow for, and expect, much wider variety of interface to choose from.

Evidence that this is indeed the case was provided in September of 2014 when I received an approach from an accordion player, Ben Devoy, stating his intention to build a Wicki-Hayden reverse action autoharp using electromagnets as a damping mechanism. The introduction of electromagnets is not attractive to me — I do not want an instrument that has to be plugged in, but it probably resolves the technical challenges of connectivity and is a perfectly viable design approach. I have corresponded with Ben at fairly regular intervals since this time; he is clearly having a frustrating time getting the damping to work, though he seems to be gradually overcoming various problems steadily. I was very glad indeed to hear from Ben. It is one thing to encounter historical patents, but quite another to be contacted by a contemporary, who had dreamed up a similar idea.

Melodica

Before leaving the subject of free reed instruments there is one more instrument that should be considered and classified with the set. This is the melodica (also called the melodion). It consists of a single set of reeds, blown by the player with a reduced standard keyboard layout as a secondary damping interface, much like the right hand manual of a piano accordion, though variations with isomorphic keyboards have been proposed. Smaller instruments are played from a fixed mouthpiece behind the keyboard and raising the whole unit to the mouth; larger melodicas of three octaves can be played through an extended flexible mouthpiece. There is one set of reeds only, oriented to blow, although in principle there is no reason why a draw set could not be added, and it is a common forum discussion topic amongst players. Because of the distance of separation between mouth and reed, the instrument lacks the wide range of timbral variety that a harmonica demonstrates. However, it is highly adaptive to pianistic technique. A good demonstration is given by the Danish multi-instrumentalist Jacob Venndt (Venndt, 2008) demonstrating applied jazz piano technique. Venndt uses right hand alone, his approach primarily melodic, using polyphonic inflections to enhance the melody, as a pianist would. Further, the detail of the rapid accenting and other articulation within the melody also matches that which a pianist would achieve. This is unusual for a free reed instrument; in terms of dynamics and articulation, the accordion is closer to organ technique than piano because the bellows must perform double duty: accompaniment and melody simultaneously. At one point in this clip we see the appearance of the Andes Melodica; based not on freed reeds but an air reed mechanism. This gives a completely different sound, and also a reduced range of two octaves.

The melodica has a history of usage within reggae, and makes occasional appearances in other genres; for example, Steve Reich used the instrument as source sound for *Melodica* in 1966. Generally however the instrument does not tend to be taken very seriously; the cheap build quality of the majority of instruments and the small-sized keys probably account for a good deal of the reasons for this — but there is no principled reason to take the design any less seriously than, for example, the *sheng* or the accordion.

The instrument has a growing following and a number of people working to develop both the instrument, and musical perception of it. The Japanese composer Makoto Nomura is an example of such. The instrument is very popular in South East Asia, where it plays a central role in music education. Nomura describes his early passion for the instrument which developed directly from his primary school experience; his frustration at the lack of availability of professional standard instruments, and his eventual return to developing the instrument for a contemporary classical ensemble setting (Nomura, 2009).

The performances of Jacob Venndt persuaded me to look at the market, and I found three octave examples to be so inexpensive (less than £20.00) that it was impossible to resist buying one. The instrument, when it arrived, played well enough, but with some mis-tuning. Fortunately free reeds can be tuned relatively easily, though it is a time consuming process, and after this it played with an even response and tuning throughout its range.

Playing the instrument was an immediately rewarding experience, which complemented the Raph effectively, because it allows expression for the slightly different pianistic training given to the right hand in an effective context of continuous sound. The link between breath and accenting was as precise as the Venndt footage suggested — the keyboard almost feels velocity sensitive. Its appearance (an unfortunate bright blue plastic) left a lot to be desired however. Painful experience of prototyping has taught me of the importance of appearance of musical instruments in gaining acceptance in the musical community. A tone wood housed variant is made and sold from www.melodicas.com, and the sound characteristics described as much improved. Co-incidentally I was at a crucial point in developing 3d rendering skills for Raph prototyping when this bright blue plastic instrument arrived, and this seemed like a good opportunity for a start-to-finish test of drawing skills, applying; measuring, rendering in 3d, separating into components and printing 1:1, band sawing all individual components before assembly. This had the desired effect on the appearance, and was also extremely pleasing in terms of improvement in sound quality; the projected tone is richer and the feedback the instrument gives to the player much livelier. The 3d renderings of this design idea are included within the digital assets which accompany this written documents, together with an overdub recording of Raph accompanying melodica, which clearly demonstrates the different training given to left and right hands effectively deployed on the respective instruments.

String Arrays, String Arrangement and Distinction

Since the patent and general direction of research originated from the idea of a keyboard (a secondary damping interface and its application to the existing autoharp) we did not discuss the detail of the string array in the first chapter. Recall from this account, that the damper bars damp each octave occurrence of a pitch and that the remainder of the accuracy of pitch is given by the right hand technique upon the string face, the string spacing is relatively narrow (though there is variation — average 1/4” or 6.3mm) in order to maximise the number of strings to available space. Further, since the strings are arranged in a flat array, held facing away from the body, there is little to distinguish individual strings. There are two parts to this problem then:

1. Optimising string distinction because of the narrow spacing
2. Optimising orientation within the interface; recognition and isolation of pitches, and pitch groups.

Providing distinction to individual strings is a problem common to all large string arrays, and the purpose of this section is to analyse effective strategies on related instruments, and to assess the potential for their application to the Raph/autoharp.

Changes to the Autoharp String Array Meme-Set in Response to Keyboard Integration

The Raph prototypes share a common intent with the chromatic variant of the autoharp, which is to provide for the possibility of complete chromaticism. Though described as a large string array, 36 strings is still a relatively small number, and the autoharp takes a strategy of prioritizing greater strength in certain keys whilst compromising others. Through the prototype progression, the Raph string tuning arrangement has diverged from the strategy taken by the autoharp, and it is worth prefacing this discussion by understanding the expression of this selective pressure within the prototype series.

Figure 34. Diagram of string pitches used on a standard commercial 36 string autoharp

The diagram above shows a pitch range from a 36 string chromatic autoharp. Despite having immediate reservations regarding this system, I decided to retain it for prototype 2. A great deal of thought will have been put into these choices, and it is prudent to innovate from a position of practical experience of the incumbent system, using its design intent as a reference point.

I suspected that I would be dissatisfied with the bass, and this proved quickly to be the case. Secondly, I was rather puzzled by the choice of notes to be omitted from the next octave (above the bass), and once again this proved a frustration — particularly irritating was the missing G sharp below middle C for melodic playing. Lastly, I favoured increasing the number of strings and moving to a system of complete chromaticism. I suspected that the first two points might conflict with this desire, and this also proved to be the case.

The original system appears to be designed to give the impression of a chromatic range by providing complete chromaticism from middle C, and then by gradually removing increasing numbers of notes towards the bass range. Beginning with the G#, notes below are gradually removed to leave strength in a particular range of key signatures. Whilst I share the vision of the design intent, the means of implementation does not suit the Raph. The autoharp system is sound, if the intent of the player is primarily oriented to harmony, but the Raph needs a fully chromatic melody range to match the increased potential provided by the keyboard, and a stronger bass range.

Prototype 3, based on an Oscar Schmidt autoharp, also has 36 strings; but using slightly different gauges makes a different set of compromises. Instead of gradually removing more and more notes as we descend through the octaves, a distinct interval split is introduced between bass and melody range. The new, fully chromatic melody range begins from g to c’’’ (using Helmholtz pitch notation) thus matching the common melodic range of a violin/mandolin (to 3rd position 3rd finger E string). This gave access to a classical and folk repertoire from violin and mandolin, which could be read immediately, and it also provided sufficient chromatic melodic compass for jazz. It also reduces potential for “muddiness” caused by closed triads in the lower octaves. Six strings remain for the bass range, and are tuned E, G, A, B, c, d providing half of the circle of fifths (though these could be varied) with an interval of a fourth between bass and melody ranges.

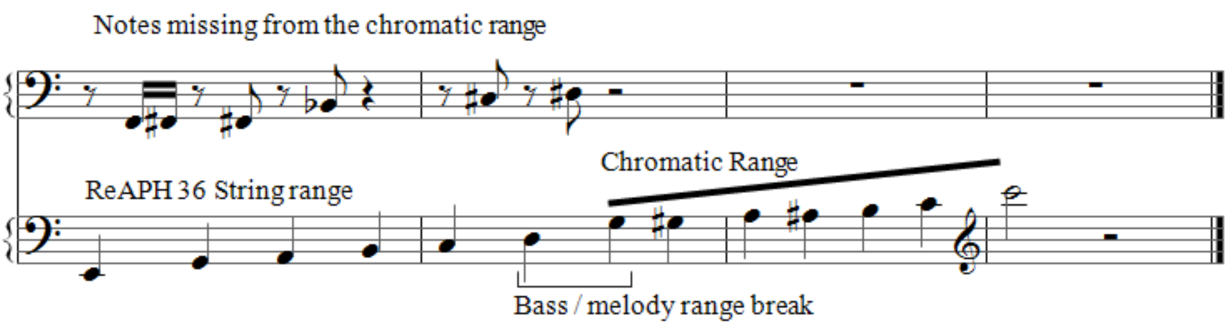

Figure 35. Diagram of Pitches used for Raph prototype 3 (36 string)

Quick access to the damper bars on this prototype was enabled through a hinged mechanism held with a clip. This quick release mechanism, it was envisaged, would allow alternative damper bar sets and provide the potential for the bass strings to be retuned to an alternative 6. In the event, I did not use alternative damper bars — this particular selective pressure was superseded by the need to prioritise effective harmonic damping (considered in the next chapter), so the clip mechanism was removed on the next prototype and a simpler more permanent mechanism applied.

The plan for Prototype 5 (42 strings) added three more strings to the melody range extending up (D''' included) and down (includes F♯), and three more strings to the bass range.

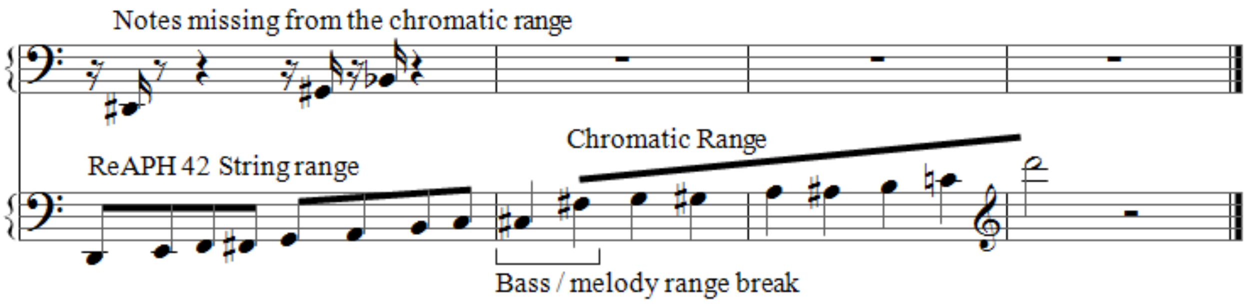

Figure 36. Diagram of Pitches used for Raph prototype 5 (42 strings)

The eventual tuning turned out slightly different because, upon testing, I considered that the low D had not been well enough achieved, and that the instrument would be better rendered from a low E. The three missing notes are F#, C# and G#.

A further 3 strings would be needed to render the bass range completely chromatic — a total of 45 for a completely chromatic instrument. Complete chromaticism does not necessarily imply a balanced instrument however, because this design pressure has to be balanced against issues of spacing and range. Initially I did not think it desirable at all; a significant restrictive factor is the span of the right hand between bass and melody range using a technique known as a “pinch”, using thumb and (usually) first finger. However, I am more sanguine regarding this factor following the long process of preparing the arrangement for, and recording Debussy's *Clair de Lune* (Brissenden P. G., 2012). The arrangement called for repeated accurate pinches at the edge of my right hand stretch-compass, and the right hand responded by developing a new kind of “spread pinch”, beginning with the thumb and interrupted at a more comfortable stretch by the melody note. The technique felt very natural for the *rubatic* shaping required by this musical material, but might cause rhythm dislocation problems in different repertoire; it brought to mind the playing of Paderewski, renowned as representative of the older romantic generation of pianists, who commonly played with non-co-ordinated hands (most commonly the melodic note was delayed and sounded after the left hand).

In light of this experience I now wonder if a chromatic bass octave might not be viable, even desirable, after all. But a second restrictive factor is my determination to include a low D at some point in prototyping. Low D is highly desirable for folk genres. 11 strings above this pitch, rather than the 8 agreed for prototype 5, might still isolate the low D string in terms of stretch, for playing in the very genre which

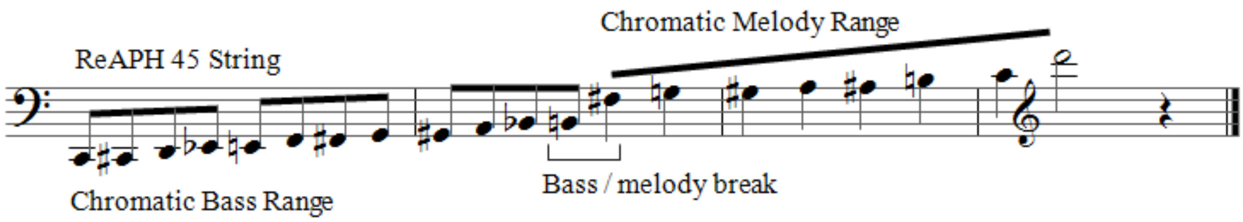

Figure 37. Proposed Pitches for Prototype 6 (45 string)

requires accurate rhythm.

The arrangement above is a compromise, which offers a nine string spacing above the low D, which might be reasonable, but this would depend on achieving the low notes well in light of further improvements to the harp body.

The more I considered this area of practice, the more I concluded that it is likely to continue to display variability across individual instruments, depending on technique, hand size and genre engagement. Commissioned autoharps from luthiers already display considerable variation, and luthiers are used to responding to individual customer demand.

Figure 38. The Zimmermann Concert Grand: the largest commercial autoharp ever produced (Harrison, 2004) with permission

The largest autoharp ever manufactured is the late 19^{th}-century Zimmermann concert grand (shown above); measuring 51cm across, it has 49 strings; and is thus a precedent for an instrument with a compass that would enable a complete chromatic tuning based on the principle of an interval split between bass and treble. This instrument also provides an illustration of the most straightforward way to provide a degree of string distinction (for recognition) — simply draw a keyboard to illustrate the string surface.

String Distinction

Though the tuning of traditional autoharps, and my vision of a Raph tuning differ slightly, and there is likely to be variation, there is nonetheless, a general principle; all systems seek to optimise chromaticism, the intent (and the ideal) is a linear, chromatic string array, which may be complete (minimum 45 strings for the Raph), or compromised, depending on the size and number of strings. As we turn to the issue of string distinction, we can dismiss from the sphere of influence large string arrays that do not conform to this principle, because these arrays provide distinction to individual strings by non linear pitch placement; examples are chorded zithers and the fretted concert zither.

Frame Harps

Distinction of individual strings on all frame harp string arrays is assisted by the advantageous playing position; frame harps are played from a side orientation, giving the player a line of sight across the string with each hand in view, engaging the strings from a different side of the string array. There is also a generous string spacing enabled by the instrument's large size and strings may be coloured differently to provide asymmetric pattern orientation. Instruments are capable of melodic/harmonic combination through isolation of combinations, which are plucked together; strumming is not central to technique on frame harps and is rarely used.

Figure 39. Erard Pedal Harp (teatermuseet, 2008)

Status: Creative Commons

The intent of the instruments is linear spacing, as it is for the Raph/autoharp, but true chromaticism is problematic. Simpler harps (and earlier historical harps) do not attempt chromaticism. The instruments are strung in a 7 note diatonic format, and rely instead on retuning of individual strings for key change.

Figure 40. Lever Harp (levers close up).

Selective pressure for the frame harp to achieve chromaticism resulted in two separate lineages. One branch retains a 7 note diatonic string tuning, and is always straight strung, relying on colour distinction of strings to provide recognition within the seven strings, and mechanical means to introduce chromaticism. Greater chromatic flexibility is given by increasing the ease and speed of retuning through moveable bridge mechanisms. This has resulted in two common forms, the lever harp and the pedal harp. Moveable bridges on lever harps (called sharping levers) are coupled to individual strings, and enable each string to be moved up or down by a semi-tone. Pedal harp mechanisms allow a similar three-way movement — the string can be raised up to two semitones, in addition to the open position, but the pedal mechanism is coupled to all octave occurrences of a pitch. The more expensive, orchestral pedal system is often held to be superior to the lever harp, but in fact each has advantages, and is suited to a different range of genre engagement. Because levers engage individual strings, specific combinations that differ across octaves are possible. This is an asset in folk melodic/harmonic combination, for example, where particular ornamentation can be set for the melody range, which is different to the lever settings for the chordal accompaniment. Pedal harps have the advantage of speed, and complete retuning across the instrument given by a single mechanism; this gives the appearance of seamless modulation and engagement with chromatic repertoire.

This 18th-century innovation is slightly predated by a different branch of frame harp evolution, which achieves chromaticism by enlarging the string array to include all of the chromatic notes. Straight strung chromatic harps exist, but are rare because string distinction across 12 semi-tones is difficult to achieve, and difficult for the player to address effectively without disastrous dissonance occurring. The triple harp is one solution: it improves the interface by providing separate rows of strings. Two outer rows of strings are strung diatonically, accessed separately by each hand, and an inner row (the black notes) is accessed by both hands. The formulation first arose in Italy in the 17th century, was subsequently widely adopted within Wales, and became a characteristic national instrument (Bowen, 2011). It achieves string distinction through an interface similar to the traditional keyboard layout. Despite the keyboard-like appearance, the interface has limited immediate adaptive potential for keyboard technique because of the different player orientation. Whilst a keyboard player understands where all the notes are, and is able to translate chord and scale shapes to the new interface, only the left hand is oriented correctly from bass to treble. The interface has many advantages, but its principle disadvantage is that it requires a lot of strings (and a lot of tuning).

A simpler solution built by Pleyel and Wolff in the 19th century is the cross-strung chromatic harp (shown above). The keyboard-like interface is achieved in this formulation through two string courses strung at opposing angles, which cross in the middle. An alternative symmetrical arrangement was also proposed based on cross strung whole-tone scales, providing an interesting parallel with the Janko keyboard arrangement, and would be the logical arrangement for a Raph Janko formulation (should application of the technique prove advantageous).

41.Modern Cross Strung Harp (Pleyel and Wolff design)

(Maloninski, 2006). Status: Public Domain

Clearly, application to the Raph would not look like the frame harp in the picture. The angle of crossover here is very steep indeed, and strumming across both surfaces is only possible at a very small intersection. This is not a problem for a frame harp because technique relies on pluck — the instruments are strummed only very rarely. The Raph angle would have to be sufficiently shallow as to allow a large intersection where the strings are nearly level, with a significant distinction appearing to the player only at the toe bridge. Such a small distinction, and the complex measurements needed to create it, might seem to argue against any significant advantage. However, this is a viable design strategy, and has the advantage that it does not rely on line of sight.

The overwhelming majority of string instruments appear to be strung with parallel string courses, such that the spacing between the strings remains constant throughout the length. This appearance is very often an illusion however; guitar, violin have a subtle draw in from the wider bridge, to nut end of the instrument. This can be seen on the violin when viewed directly from above. The variable string spacing provides maximum width and string distinction for the point of sound production (pluck, strum or bow), and a narrower spacing at the fingerboard.

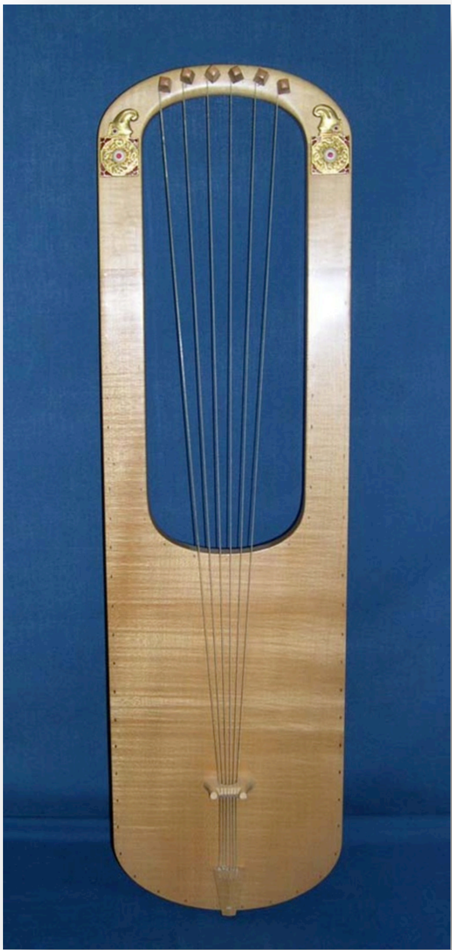

Figure 43. Reconstruction of a lyre from the Sutton Hoo ship-burial 1, Suffolk (England). Lyre reconstruction by Dolmetsch. (Plunkett, 2007)

Status: Creative Commons

Large string arrays, such as frame harps, tend to be strung in parallel arrays and autoharps follow this pattern. An example of an array that breaks the rule of parallel appearance is the lyre. The purpose of the variable string spacing here, is to provide a strum surface at the bridge, where the strings are narrow, which changes to a string spacing set for comfortable finger width at the nute.

The six-string instrument on the left is reconstruction of a 7th-century instrument; there are also similar examples with 7 strings, and larger instruments with a more subtle variable spacing, and also some examples that display parallel string spacing.

Figure 42 String Spacing on a violin (Bill, 2013)

Status: Creative Commons

The idea of the interface is that the left hand sits behind the strings and damps different string combinations (like a damper bar). The remaining strings are sounded through a strum much lower down the string face, where the strings are closer together. Corwen Broch (Broch, 2010) provides a good demonstration of this technique.

The purpose of adopting a variable spacing would be different on the Raph. It would aim to provide wider string spacing towards the toe end of the instrument, suitable for more precise pluck technique. The angle of separation needs to be considered carefully against the design constraints of a large string array, and would need to be much narrower.

Overall there are three possible techniques to provide increased string distinction and recognition that are commonly found on large string arrays:

1. Distinction through colour contrast of individual strings
2. Distinction through variable spacing
3. Distinction through cross string techniques

Combinations of Strategies

If we compare an acoustic guitar strum surface of six strings, the string separation at the bridge is around 11–12mm depending on the model. An autoharp typically provides 1/4” string spacing (6.3mm). This quite a narrow spacing, assisting strum but hindering string isolation and a variable spacing might assist here. On a large array, this variable spacing will assist distinction, but not recognition, because continuous variable spacing will not introduce any recognisable asymmetry.

The pianist's instinct is to try to make the black notes stand out from the array, perhaps through colour coding and/or cross string techniques.

The Raph player does not have an advantageous line of sight across the instrument as there is for the player of the frame harp, which would seem to argue against a strategy of colour coding for string distinction. It is advantageous to develop technique that does not rely on sight at all with reference to the string interface. But this is true to a very large extent for any musical instrument, particularly where the issue of sight-reading becomes a part of the frame of reference. Good sight-reading is characterised by solid and unbroken engagement with the page with acute peripheral awareness of the instrument, bad sight-reading is characterised by hesitation in the music stream given by a distinct shift in attention from page to playing interface. This is often not noticed by the novice player, but painfully obvious to tutor and audience alike.

Developing sight-reading skills on the piano is highly dependent on the asymmetry of the keyboard interface — without looking down at the keyboard a player can move by touch to the correct position, and no notes need be sounded in this process. Nevertheless, keyboards allow for both the tactile navigation, *and* sight (the keys are colour coded). Isomorphic symmetrical interfaces often distinguish reference keys by indentations on the surface of the keys (there two such on the F and J key of a computer keyboard), and also code using visual stimuli. Guitar fretboards are nearly always inlaid at fret intervals to allow for visual orientation. It seems that many complex interfaces allow for a combination of visual and tactile stimuli.

How precise does the right hand technique need to be on the Raph? Given that much of the precision is provided by the keyboard and the damping mechanism, does it matter if surrounding, damped-strings are caught in the strum/pluck action? The answer to this very much depends on the mode of engagement. For rhythmic chord and melody combinations absolute accuracy is not a factor, and this is indeed one of the great strengths of the instrument. But the more melodic the playing, the more precise the right hand needs to be to bring out the true beauty of the melody; catching surrounding damped strings results in added noise — exposed during melodic playing. It is in this aspect that I really benefitted from contact with autoharp players, and particularly from one to one contact with Mike Fenton. For autoharp players, working with chord bars, dissonance is always only a slip of the right hand away — and there is a noticeable difference in the level of precision of good players.

It is fair to say that the linear string array of the autoharp presents poor visual and tactile orientation compared to other large string arrays. To what extent can we enhance the design in order to satisfy the demands of this particular selective pressure?

Distinction Through Colour Contrast of Individual Strings

Despite the lack of a direct line of sight whilst playing, colour contrast may be useful. A potential candidate for this purpose are coated guitar/bass strings manufactured by the company *Dr*. The coating is held to produce desirable sound enhancement characteristics, extend the life of the string and to minimise plectrum noise. These strings have the advantage of providing colour distinction, and are available in a range of colours — including black. However, these strings are extremely expensive, and really prohibitive for prototyping purposes. Acoustic guitar, coloured bronze round wound strings are available relatively cheaply however, sold from a number of different internet outlets as “rainbow” guitar strings. These would provide colour distinction for the bass range, but the plain steel B and top E gauge strings are not coloured, and unfortunately these gauges form approximately half of the Raph/autoharp.

Frame harps, based on nylon strings and wound nylon cores, offer an alternative. On these instruments the treble plain nylon strings are readily available in different colours, but the lower steel wound strings are not. This is altogether a frustrating set of findings for prototyping purposes — there seems to be no easy way to assemble a reasonably priced set of strings to provide colour distinction in order to test the effectiveness of the strategy. A further alternative later discovered at first hand experience is the difference in the string design for guzheng, koto and other related instruments. Contemporary string design for this instrument, is that a steel core is then wound on the outside with nylon; an unusual combination, which leads to a unique sound. These strings also appear to be very loud.

Distinction Through Variable Spacing

Even variable spacing (meaning each string is strung to the same variable spacing) is a reasonable principle on a small instrument such as the Anglo-Saxon lyre discussed previously. For a large string array such as the Raph/autoharp, with the added complication of damping, the application is difficult, but not impossible. Variable spacing — a different space at the dead end (nut) and toe bridge, always turns the angle of the string away from the origin with respect to the adjacent strings. But variable spacing is also applied asymmetrically on some larger lyres and is used as a strategy to provide distinction of individual strings.

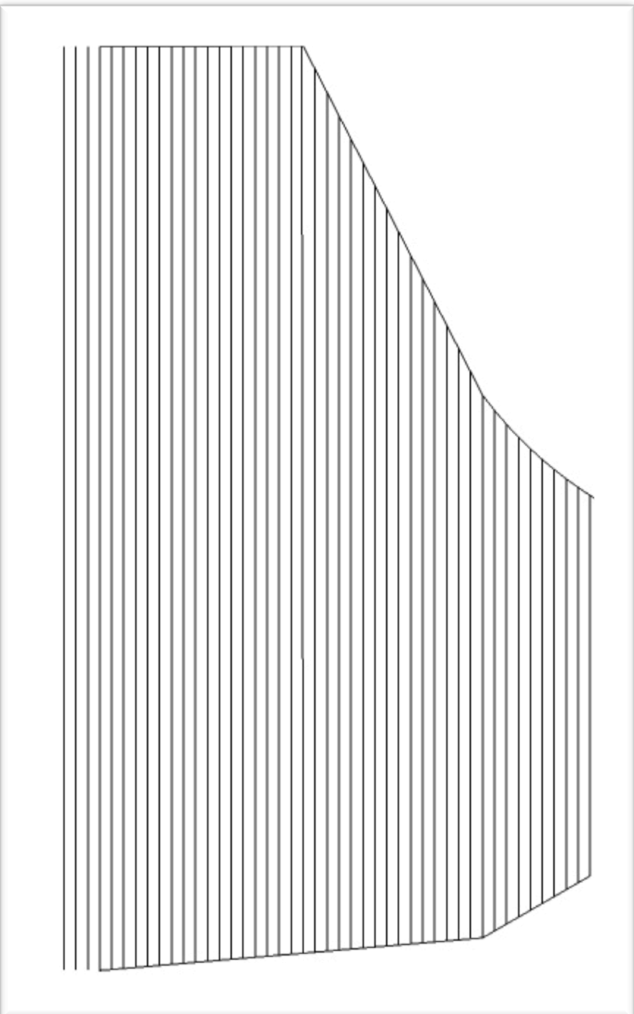

Figure 44. The original string specification for prototype 6 (45 strings)

The projection left is the original string specification for prototype 6, using a 1/4” (6.3mm) parallel string spacing and autoharp strings, with three strings added to formulate a fully chromatic range. The scale length of the bass strings is severely compromised and one of the ideas discussed is to use a longer string specification closer to guitar scale length. This change is included in the development of this set of design pressures because it assumed to encompass all of the features (such as improvement of the low notes) so far discussed.

The projection below is an attempt to provide asymmetric variable spacing to increase string distinction and recognition simultaneously, by distinguishing the black notes. The projection begins from the same point — the high D strings are identical on the two projections. Parallel ¼” spacing is then applied between white notes, and when moving white-to-black notes. Each black to white movement uses variable spacing, beginning from 4mm at the dead end and widening to 7.5mm at the toe end.

The scale length is calculated using guitar gauges using a 650mm scale length. The extent of the compromise to the high D string became clear during the process of this calculation; already perilously short, the pitch change from B through D is clearly accomplished as much through an increase in tension as a shortening of scale length. The eventual discrepancy on the high D is 192.4mm (calculated) to 202.2mm (measured). These calculations placed the planning for prototype 5 in a new perspective, and fully explained the flat refusal of my collaborator on this prototype (luthier Alec Anness) to extend above a high D). Some other variances are present in the projection. The lower string spacing — both variable and parallel, allows more space for increased string gauge, and the longer strings have a wider toe measurement for the variable spacing of 8.5mm producing a similar 7.5mm in the playing range. There is also a 9mm gap between the bass and treble range.

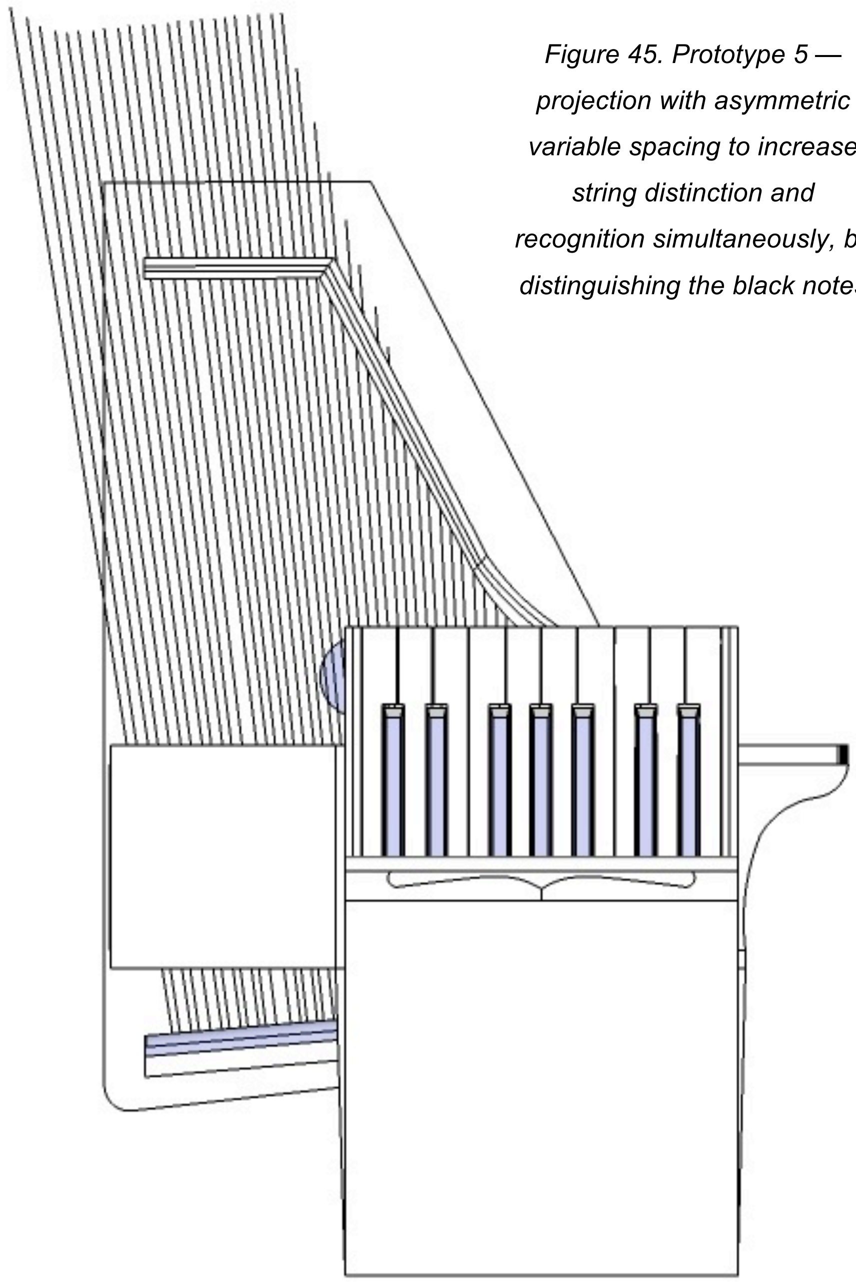

Figure 45. Prototype 5 — projection with asymmetric variable spacing to increase string distinction and recognition simultaneously, by distinguishing the black notes

Placing this new specification onto the body of prototype 5 reveals that many of the desired objectives are achieved. The string surface width at the dead end remains comparable to the original measurement, particularly considering that this rendering contains three more strings (prototype 4 specifies 42 strings). The width after the damping mechanism also remains comparable, and the widening at the top of the instrument is as great as can reasonably be expected. The string length at the toe end is extended by the desired amount (specifically: the extension should be minimised because right hand contact should be in the final 1/3 of the string). The success of the specification with regard to string distinction is far more difficult to assess. At the size printed for this text, the black-white patterning can be discerned after study. Printed at 1:1 the black-white patterning does become clear, but perhaps not “at a glance”.

Significantly, as a player, I was attracted to the fan shape immediately, and could imagine it on the instrument during playing. I found it aesthetically pleasing from a playing and visual perspective. There are several disadvantages to this projection from the perspective of distinction only. Firstly, it only widens the spacing 5 times per octave. This could be reversed, and the measurements could be tweaked retaining the asymmetry, so we could widen the spacing 7 times per octave as an alternative.

The asymmetry would be immediately lost however, should we attempt to reflect a whole-tone Janko keyboard layout in the string array, where a 50/50 division between parallel and variable would now reflect the keyboard. Or we might abandon this asymmetry and use this strategy to produce similar variable spacing throughout the array. Overall, the principle that the technique is possible, is established.

Distinction Through Cross String Technique

This strategy produces individual string delineation and unlike the variable spacing, it is almost impossible to illustrate effectively using 3d rendering techniques. The principle is simple, thinking first from a pianistic perspective, the black notes would be cross strung such that a near flat surface is presented to the right hand immediately above the damping mechanism, and raised at the toe end; white note orientation is not changed and is left flat. The optimum position will vary from string to string in order to render the crossover point similar with respect to the end of the damping mechanism. The main problem with this strategy is that the string surface presented to the damper bars is no longer flat and dampers of specific lengths would have to be created for each string. Considering the measurements (likely to be 1, 2 and 3 mm difference) and the nature of damping felt, this is likely to be a time consuming process to implement. It would not be possible to experiment with different damping positions to improve harmonic damping, so this problem would have to be solved prior to implementation. This aspect renders this strategy rather unattractive.

Overall, all three strategies have the potential for incorporation into prototype 6, but implementation is not straightforward. The first (and simplest) method, that of simply drawing in a keyboard, such that it is visible to the player at a glance from the playing position, remains a practical possibility that can be easily implemented.

Alternatives to Zither Pins

Finally we return to the discussion of alternative tunings. The possibility of rapid retuning would be greatly assisted by fitting geared machine head mechanisms as opposed to simple zither pins; machine heads are undeniably superior in engineering terms. Machine heads would be difficult to fit to an autoharp configuration, and would change the look of the instrument considerably. However, such an innovation *is* possible — some recent South American frame harps use machine heads in a double row with the strings fed into the void between them and a similar strategy could be deployed on an autoharp body.

Figure 46. Paraguayan Harp using geared machine heads (Griffindor, 2009)

Status: Creative Commons

We must balance the possible gain in design terms against establishment conservatism, because this step would possibly signal a revolutionary departure from expectations of autoharp body design. Prototype 3 was undoubtedly viewed as evolutionary rather than revolutionary at the UK autoharps meet at Mickleover in 2012, but all the tested design changes, excepting the precise pitches to which the compass of strings is tuned are upon the reverse damping action — the prototype is based upon an otherwise un-modified Schmidt autoharp.

Establishment conservatism can be quite extreme within musical systems, and often difficult to fathom; geared machine heads have for some time been commercially available for violin and are clearly superior to the friction pegs that they are designed to replace. Implementation would render the fine tuners at the bridge redundant because the precision is given by the gearing. Manufactures have taken great pains to produce the new mechanism so as to appear exactly like a traditional friction peg, but despite all these advantages, they are rarely implemented. There might be an argument against implementation on the violin from a weight and balance perspective, but no such argument exists for the 'cello, where the device is *equally* rarely implemented. In fact the arrangement of friction pegs at the nut, and fine tuners at the bridge is similar on violin, viola and ‘cello and then changes for the double bass, where geared machine *are* the accepted norm. This change is highly advantageous given the large size of the interface as it allows for simultaneous sounding of the strings whilst tuning.

The disguised violin machine heads would be make a perfect replacement for zither pins, the turning head is in line with the winder, rather than offset at 90 degrees like a guitar machine head, and the “alien” hand-turning heads could be hidden at the back of the toe pin block with only the string turning heads showing — so the appearance to the autoharpist would be relatively unchanged from the top of the instrument. Violin machine heads are however, prohibitively expensive for initial prototyping purposes, and probably for the foreseeable future.

Summary of Design Criteria Expressed as Selective Pressures on the Raph Prototypes

During this analysis we have constructed narratives around various design pressures, exploring their expressions upon various instruments, their relationships and their potential for application to the Raph. We have seen that many of the design principles that are desirable conflict with each other.

During the early stages of prototyping, the fundamental design questions were expressed as:

Playing interface

1. Comfortable keyboard playing position for left hand whilst simultaneously providing:
2. Comfortable strum/pluck position for the right hand.

Design considerations

1. Maximising the playable string surface
2. Providing and effective reverse damping mechanism

As a result of the previous analysis, these fundamental questions were considerably refined into a set of design criteria.

The criteria for inclusion in this list is that the parameter is desirable, can be expressed as an independent meme, and understood as such. We cannot allow the complication of relationship or competition, but we can take account of it by expressing each, in a manner akin to an intended learning outcome. We are then provided with a checklist, and a point of departure for discussion and the prototype series can be measured against each of these through the various stages.

At the end of the prototype process the instrument should provide:

1. The optimum playing position (defined through the patent claim as expressed in the patent claim re-write of 9th August 2011)
2. A keyboard that conforms within the range of expectations of behaviour for a full sized keyboard in terms of appearance and touch & feel (this may allow for a Janko alternative which is compatible with the design).
3. The most efficient and practical pulley and string system.
4. Optimum balance of key movement (and return) providing effective force exerted by the key through a pivot point (and pulley and string mechanism) on the damper bar to un-damp strings and an effective return mechanism
5. The optimum number of keys (range min: 12 max (practical) 18)
6. Effective string and string harmonic damping
7. Minimal noise from the keyboard and damping mechanism
8. Effective integrated amplification
9. Optimised playing space on the string surface (particularly in the high treble)
10. Optimised string tuning, gauges and number of strings
11. Optimised access to mechanisms for maintenance
12. Optimised string distinction, considering variable spacing, visual (colour) spacing and cross string techniques
13. Optimised tuning (winder) mechanisms including geared machine heads

There some other acoustic improvements which are also considered for inclusion in the prototype series. These have not been a focus within the previous chapter because they do not form part of the keyboard and damping interface design, but they do constitute basic improvements to the sound of the instrument, which were studied and considered in some detail in the process of prototyping. For example: on most commercial autoharps the toe bridge is not directly coupled to the soundboard, because both the dead end nut and the toe bridge are placed over the frame material[7]. This provides a poor coupling mechanism of bridge to top plate. Considered together, we can summarize these as:

14. Optimised top plate design (to provide a suitably radiused dome or arched structure).

15. Optimised depth and volume of the resonating chamber

16. Optimised coupling of bridge and top plate; optimised spacing behind the bridge — particularly with regard to the bass strings, to improve the lower bass projection (range: add at least two inches of top plate space around the bridging point of the bass strings)

These design principles are abbreviated below in order to allow quick recognition within tables in the next chapter:

Action

1. Playing position
2. Keyboard: appearance and feel
3. Pulley and string system
4. Key pivot point to damper coupling
5. Key range
6. Harmonic damping

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[7] In strict terms a bridge is defined as a member which transfers the vibrations of the strings to the soundboard or other resonant body whilst a nut is defined as a string bearer fixed onto a solid member which is not responsible for transferring vibrations to the resonating body, therefore both string bearers should be referred to as nuts. The application of "bridge" to the toe-end string bearer as standard throughout this text reflects the fact that design practice is mixed, but more ambitious acoustic design results in the toe end string bearer placed over the resonant body (therefore becomes a bridge). This is also the developing design intent for the Raph.

7. Minimal noise
8. Integrated amplification
9. Playing space on the string surface
10. String tuning and range
11. Access for maintenance

Harp

12. String distinction
13. Tuning mechanisms (winders)
14. Top plate
15. Depth and volume of the resonating chamber
16. Optimised coupling of bridge and top plate

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