Target Motion Analysis Visualisation.

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Abstract

Target motion analysis (TMA) visualisation is used by naval ships to locate targets around ownship when more accurate methods such as active sonar are not viable. TMA utilises an array of data, the main source being passive sonar, and results in an almost infinite number of possible solutions. These solutions must be filtered by the TMA operator to identify the most probable or hazardous solutions. Current TMA visualisation solutions do not effectively utilise visualisation theory and require an operator to take a mechanical instead of cognitive approach to target tracking. This paper presents a novel approach to target motion analysis visualisation based in established visualisation literature. A variety of visualisation techniques have been explored through this research, with a focus on reducing cognitive load of the operator. These visualisation techniques were evaluated through "expert review" and the results presented.

1 INTRODUCTION

Target motion analysis (TMA) is a process by which targets around a naval vessel are identified and tracked. This tracking is an approximation of the targets location based on vast amounts of low signal-to-noise data. With the scope of the data involved in TMA some method must be applied to reduce the cognitive load on an operator.

Visualisation is an interactive, computer-supported, visual representation of data to amplify cognition. Cognition, in this context, is the acquisition or use of knowledge (Card el al., 1999). The aim of visualisation is to aid in discovery, decision-making and explanation. By rendering the data into a visualisation, the information undergoes a "qualitative" change that encourages the use of the advanced pattern-recognition capabilities of the human "eye-brain" system. The high cognitive load of the TMA process, the problem of identifying probable or hazardous solutions in the space, therefore, make it an ideal process for the application of visualisation theory. By leveraging the volume of work already done in the field of visualisation, by identifying important visualisation techniques and how these techniques aid cognition, we can potentially reduce the cognitive load placed on a TMA operator.

The remainder of the paper is organised as follows: the rest of the introduction section explains the problem of TMA. Section 2 covers the literature review into visualisation theory. In section 3 the visualisations we have investigated are documented. Section 4 covers a testbed developed to test the visualisations and section 5 is a discussion of the research.

1.1 Target motion analysis background

In situations where active sonar is not a viable option, TMA provides a means to track targets using bearing data received from passive sonar (Streit and Walsh, 2002). This is primarily used in naval vessels where tracking of vessels around ownship is essential in deciding an appropriate course of action. In the naval terms used in TMA, ownship refers to the current observation platform for the bearings. A bearing is essentially an indication of direction. Target refers to a single vessel, the source of bearings, being tracked by ownship (the terms *target* and *source* may be used interchangeably). The problem space is the set all possible scenarios of the location and movement of a target confirmed by the bearings. Therefore a solution is considered to be a single resolution to the location and movement of a target based in the problem space.

Passive sonar, the main source of data for TMA, utilises an array of hydrophones and a technique known as *beamforming* to infer bearings corresponding to a tracked target. Beamforming works on the assumption that every naval vessel radiates a factor of noise from the engines and other heavy mechanical processes, to which the hydrophones of ownship listen for from the target vessels. The passive sonar process takes this radiated noise signal, adjusts for any ambient noise from the ocean and ownship self-noise, and approximates a bearing based on signal strength received by the individual hydrophones. This signal received by the hydrophones commonly has a low signal-to-noise ratio due to the background ocean noise, ownship noise, and ambient reflections (Waite 2002), and in turn the bearings have a relative uncertainty factor associated with them.

Much work has already been done investigating potential ways to increase the certainty factor associated with bearings (Maranda and Fawcett 1991; Martinerie and Forster 1992; Cadre and Trémois 1996). Still, it is impossible to completely remove the uncertainty from a bearing due to the nature of the data itself. Even when assuming certain bearing data, there is still the problem of discerning solutions from these bearings. The research being conducted here is not concerned with determining bearings based on uncertain data, but is instead examining the solutions that can be discovered from bearings assumed to have a relatively high certainty factor.

This bearing data alone cannot be used to adequately track targets as it represents only the relative direction of a target to ownship. A target is defined also by range, and speed. The three variables are interrelated, so if you can define two of these variables, the third is evident. Knowing only the bearings resolves to a close-to-infinite number of possible solutions as to the precise range and speed of the target (Tremois and Le Cadre, 1996). So in addition to the bearings data received from passive sonar, an operator can compliment the TMA process with qualifying data. A potential speed and classification of the target, for example, can be ascertained by listening to the number of screw revolutions of said target's propeller shaft. This speed and classification information can greatly reduce the problem space as solutions not supported by the qualifying data may be removed.

To perform adequate target tracking therefore, the TMA operator must reduce the problem domain down to a probable set of solutions. The data from passive sonar must be integrated over time and, to ensure an adequate amount of certainty of the bearing data, requires that at least either ownship is manoeuvring, the target is manoeuvring or both are manoeuvring.

1.2 Bearings example

Bearings are the azimuth angle from an observation platform to a target (Nardone and Graham, 1997). This is purely an indication of the targets direction from ownship, interpreted as an angle from true north. Since bearings make up most of the usable data of TMA, and as they only represent direction, they offer a potentially infinite number of solutions as to the targets range and speed. Given a set of bearings and with ownship on a fixed course, the range and speed of the target is relatively undefined.

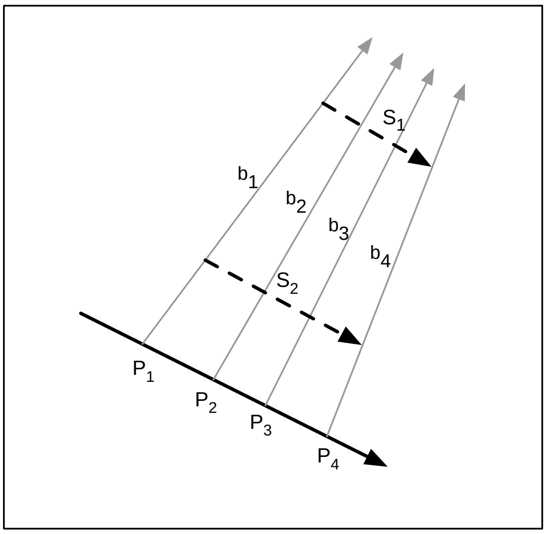

Figure 1: Simple example of bearing data

Figure 1 displays a simplified scenario illustrating the nature of TMA bearings. For this example ownship, taking a path defined by the points $P_{1...4}$, is assumed to have a constant velocity and having a regular bearings sample rate. Each point $P_{1...4}$ are equidistance and represent the point at which the bearing $B_{1...4}$ were taken. These bearings give an indication of the direction of the target relative to the point of ownship where the bearings were taken.

Illustrated in Figure 1 is two possible solutions (S_1, S_2) that can be obtained from the bearings. Solution S_1 places the target at a low velocity far from ownship's path, whereas solution S_2 has the target at a high velocity close to ownship.

1.3 Current solutions

Current deployed TMA visualisations do not effectively utilise visualisation theory or operator cognition, instead requiring the operator to mechanically find solutions in the problem space. A current particular solution according to Relf (2004, pers. comm. 2004) involves "stacking the dots". In this solution a function of the tracking data is plotted to screen in a visualisation resembling a sinusoidal graph. The operator manipulates potentiometers to adjust a suggested distance and speed of the target being tracked, which results in waveform displayed changing shape. When the waveform resolves to a straight line a potential solution is found. This is an essentially mechanical process that does not fully utilise the cognitive aspects of visualisations. Even when supported with a Cartesian plot of the solution being proposed, the operator's main interaction is with the "stack of dots". To summarise, instead of recognizing a solution based on the information being presented to the operator on screen, the operator mechanically searches the problem space for a solution.

1.4 Statement of problem

The problem of visualising TMA is inherent in that the set of possible solutions can be almost infinite. This can place a great deal of cognitive load on the TMA operator who must comprehend a large amount of information being displayed to them. Furthermore, current TMA solutions abstract the problem and force the operator not to recognise a solution but to mechanically find a solution.

The purpose of this research is to investigate the visualisation of target motion analysis. From this research a set of TMA visualisations will be discovered along with the relevant visualisation theory supporting said visualisations.

1.5 Method

Research into target motion analysis visualisation has usually been conducted with thorough knowledge of the current and past visualisations solutions. As such, these visualisations tended to be incremental changes of current designs and carry on the design mistakes of the past visualisations.

The visualisations being investigated here are taking a novel approach to their investigation with a thorough grounding in visualisation theory. While there is little literature specifically relating to the visualisation of TMA, there is an immense resource of general visualisation literature that may be applied to the problem of TMA visualisation. As a research tool, a testbed has been developed through which the visualisations are investigated.

2 VISUALISATION BACKGROUND

The intention of our investigation is to examine TMA visualisation from a background of strong visualisation theory. The literature review therefore begins with a study into what is regarded as essential literature in visualisation and, in particular, the specific field of information visualisation.

There are numerous real-world problems, such as target motion analysis, involving vast amounts of data that must be comprehended by a user. If left unprocessed, the majority of this data is incomprehensible due to the limits of human processing. Visualisation is the process of communicating through visual information, by utilising computer supported graphical representation of data that aids external cognition (McCormick, DeFanti & Brown, 1987). External cognition, defined by Rogers and Scaife (1996), is the offloading of the computational complexity of a problem to some visual representation, which otherwise would have to be conducted through mental formulation. Visualisation reduces the cognitive load placed on a user through the externalisation of the problem, so leveraging the high capacity for humans to process visual information.

There are several disciplines within visualisation; of note are scientific visualisation and information visualisation. Scientific visualisation is concerned with the visualisation of physical data whereas information visualisation is visualisation of non-physical, abstract data. The data involved in TMA visualisation includes physical as well as non-physical data; the bearings represent physical directions, but deriving a solution is a non-physical multivariate problem. For our research into TMA visualisation we have focused upon information visualisation due to its focus on data exploration.

2.1 Interaction

Interaction is a fundamental visualisation concept involving the user manipulation of visualisation. Interaction leverages the computers ability to dynamically construct a particular visualisation. The visualisation process can be conceptualised as a pipeline process, as illustrated in Figure 2, through which the raw data makes several transformations towards the final visualisation. When user interaction is introduced at any level of this process, the user may "explore more possibilities in a given time [and] shift effort to the machine by watching what happens as the controls are modified" (Stuart K. Card et al., 1999).

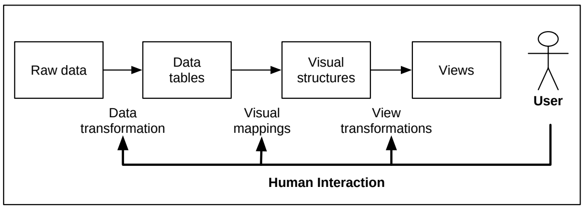

Figure 2: Interaction diagram reproduced from (Card et al., 1999)

The 1987 paper "Brushing scatterplots" (Becker et al., 1987) confers the purposes and concepts of brushing as a solution. Becker & Cleveland describe brushing as a "collection of dynamic methods for viewing multidimensional data". The key concept of brushing is the “brush”, which Becker and Cleveland describe as a "rectangle ... superimposed on the screen". User interactions with a screen input device are directly reflected in the brushes position on the display. They define a highlight technique, which selectively emphasises portions of the data within the brush using some visual distinction. Highlighting solves the "link problem", of visual association across a disparate set of visuals. By moving the focus of the brush, the data between the panels highlights according to represent associations.

For brushing to be useful, we need to show several visualisations. A paper entitled "Comparative Multivariate Visualisation Across Conceptually Different Graphics Displays" (Hinterberger et al., 1994) expands the concept of linking distinct visualisations through interaction, which the authors refer to as comparative visualisation. With comparative visualisation, several different visualisations of the same multivariate data is presented to the user, where "the goal is to find methods that are conceptually different in that they show or emphasize different qualities of an underlying data set" (Hinterberger, 1994). In a related the panel review (Inselberg et al., 1994), Hinterberger, a panellist on the review, suggests that being able to make changes in one visualisation should have a corresponding effect in the other visualisations. Such interaction lends itself to investigating how "conceptually different displays are related". Furthermore, some visualisations may benefit from manipulations that can only occur in other visualisations of related data.

In exploring TMA visualisation, we chose a set of visualisations. As Hinterberg et al. reveal, it is a logical extension of a visualisation to display the separate visualisations simultaneously; thereby allowing the user to view the effects of interactions in one visualisation in another visualisation for which that interaction was not defined

2.2 Visualisation Animation

Animation is an important visualisation technique that can increase the cognitive value of visualisations. In the context of visualisation, animation refers to the autonomous motions of the representations along the time dimension.

Animation in 3-space visualisations, referred to by Wright (Wright, 1995) as information animation, "allows a higher level of expression, [an] increase in the amount of data displayed, and a broader scope of application". 3D animation without interaction is not suited towards analysis, as the viewer is "limited to a pre-determined set of presentations and the communication of pre-conceived messages ... [they] do not support data analysis because the relationships and features have already been identified, and the information has been extracted and prioritized for communication purposes".

In a paper Nakakoji et al. (2001) explore the cognitive aspect of visualisation as well as the types of interactions with animated visualisations by users that may be observed. They built upon some of the concepts that Wright explored. Their exploration found that animation is ideal when one needs focus on the change in time-based data and in "limiting a point of view in a single aspect". They identified 3 requirements of animated visualisation through their studies. Summarised here, they are:

1) Animation needs to convey to the user the context of the changing data.

2) Animation needs to convey context in time.

3) Users must be able to control both space and time.

Nakakoji et al. have expanded upon Wright's (Wright, 1995) earlier work and quantify the benefits of animation. Their studies found that subjects respond positively to animation when used for chunking, interpreting, fore-casting, comparing, focusing and filtering data. Subjects responded negatively when compared to the static visualisation in grasping the "whole" of the data and while performing statistical analysis (averages etc.) of the data. Their studies found that while a static 3-dimensional graph can semantically represent the same information as an animated 2-dimensional graph, the interpretations of the static versus animated graph can be quite different; they have very different cognitive effects.

The techniques and issues identified by Nakakoji et al. have several applications in TMA visualisation. Since data in TMA is temporal we can autonomously play through the data. Also, since animation helps maintain context, we can use animation to transition between the various visualisations we investigate. This allows the operator to fluidly switch between various visualisations for a different perspective of the data which still maintaining a mental context of where the visualisations fit with the data.

2.3 Three-dimensional visualisations

While generally considered more aesthetically pleasing than their two-dimensional counterparts, often the actual worth of three-dimensional visualisation is overlooked in favour of the associated showiness. As Ware (Ware 2000) puts it, “it has recently become cheap to display data in an interactive 3D virtual space and so people are doing it, often for the wrong reasons. It is inevitable that there is now much ill-conceived 3D design”.

Many of the problems that lead to ill-conceived three-dimensional visualisations are due to the limits of current displays. To view a three-dimensional visualisation on a two-dimensional display such as a monitor screen, some method of projection must be used to render the three-dimensional geometry. Ultimately, some amount of geometric information is lost through this projection, reducing user’s perception and possibly distorting the intention of the visualisation (Baker 1992).

Occlusion occurs when proximal aspects of three-dimensional geometry obscure distal aspects of geometry, and is considered an important depth cue (Ware 2000). Through occlusion a user manipulating the visual orientation may discern where objects lie in relation to each other. However, occlusion may lead to the loss of visualised information as occluded objects do not contributed to the volume of data presented, reducing user cognition. Research by Wright (1995) has looked into using occlusion to improve the cognitive contribution of a visualisation. In the prototypes developed through his research, Wright uses rotation to purposely occlude certain aspects of the visualised data. For example, with the visualisation oriented to a particular isometric view, the full history of the day-by-day state of the stock market is visible. By orientating the view so that only the viewer points down one of the three axes, and so forcing a two-dimensional view of the visualisation, a user can focus on the current day's stocks only, removing possibly extraneous information.

3 VISUALISATIONS OF TARGET MOTION ANALYSIS

The purpose of this research is to examine target motion analysis visualisation from a background of visualisation theory. In this section the research explores the application of the visualisation theory applied to the process of TMA visualisation. The intent of these visualisations is to aid the TMA operator in identifying solutions in the problem space while reducing the cognitive load placed on the operator by the process. They are intended to reveal solutions that may not have been identified otherwise while reducing the number of erroneous solutions and so improving the correctness of the solutions. The following visualisations should be considered prototypes intended to demonstrate the application of various visualisation techniques.

3.1 Clustering

As the cognitive load of the raw bearing data can be somewhat overwhelming to an operator, we have investigated ways to effectively reduce the amount of data displayed at one time. Clustering is a technique to reduce the visual disparity of related marks in a visualisation, by which similar data is “clustered” into a visually larger grouping (Garcke, Preußer et al. 2000). Clustering is often used in a wide variety of visualisation problems, from statistical analysis, to vector field visualisation.

It is important to present the operator an overview of the bearings, as a good graphic need to reveal the data at several different levels of detail, “from a broad overview to a fine structure” (Tufte 1983). As Garcke, Preußer et al. (2000) state, clustering is a multiscale solution to this problem of “different viewers need different representations. Numerical experts might want to see the raw data in full detail, technological experts might want to see certain features such as vortices, whereas the management might need a simplified presentation”. Since this research has investigated other techniques, such as brushing, to addresses the need of examining the data at a high detail level, clustering addresses the need to present a broad overview.

We have used a simplified clustering model in these prototypes, whereby clustering reduces the individual bearings into a shaded polygon representation. The polygon encompasses the boundaries defined by the bearings and estimates of distance, as depicted in Figure 2. While applying this technique reduces the volume of data depicted, the nature of the bearings (orientation and boundaries) is still conveyed. Furthermore, the visualisations allow the operator to specify artificial limits on the cluster based upon estimates received from a multitude of sources considered to have reliable information. The operator may specify the minimum distance, furthest distance, minimum speed and maximum speed of the target. These artificial limits reduce the visual space presented, and so reduce the problem space the operator must consider, thereby relieving overall cognitive load.

Pseudocolour has been used on the clustered bearings to delimi-

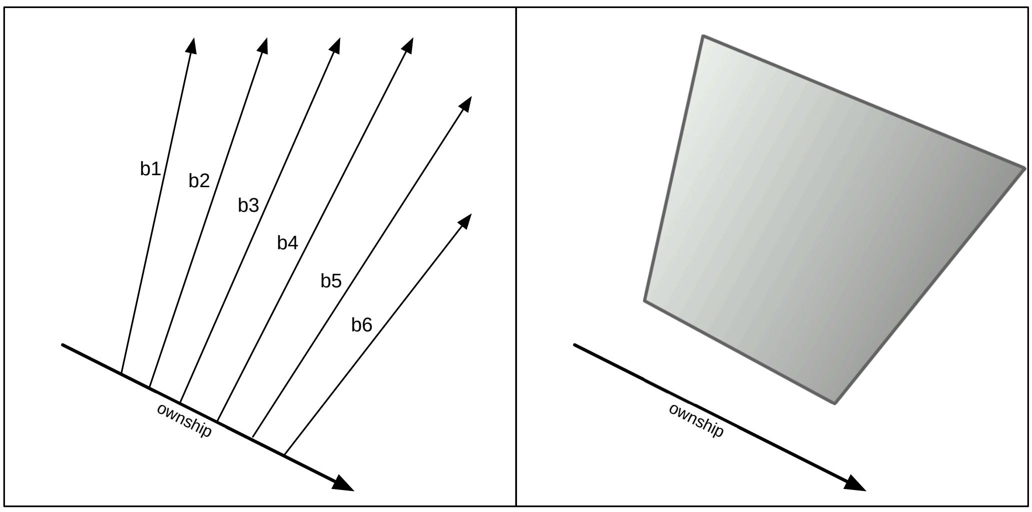

Figure 2: Left diagram is an example of bearing data, right is the bearings clustered

tate time. Each time sample is mapped to a unique colour on a spectrum. In the visualisation here, the colour of the cluster is smoothly shaded from dark grey to red. The dark grey edge of the cluster represents early bearings which progressively fade to the red edge representing the latest bearing.

3.2 Ownship-centric and world-centric view

Being essentially an indication of direction, TMA bearing data may be rendered as rays emanating from a point on the display. Different interpretations of the bearing data are apparent depending upon the chosen origin point for these rays. More specifically, whether these rays are drawn emanating from a point on the ownship path or emanating from the same single static point will yield different interpretations of the data.

Drawn relative to the ownship path suggests a world-centric view. The bearings originate at the coordinates of ownship at the point in time in which they were taken and radiate outwards towards the target. The bearings are plotted in this case on screen at the world coordinates from the point at which they originate.

Given ownship's location, in two-dimensional Cartesian coordinates, written as (r_{xo}, r_{yo}) we define a vector x_o such that: $x_o = (r_{xo}, r_{yo})$. We define a target's bearings at a particular time t, as θ_t. Given these bearings, we create a unit vector X_u in the direction of the target, such that: $X_u = [u_{xt} , u_{yt}]$. Where $u_{xt} = sin[\theta_t]$ and $u_{xt} = cos[\theta_t]$. The rays rendered in a world-centric perspective require a relative vector, being the sum of the ownship location and unit vector as $X_r = X_o + X_u$. World-centric rays originating at X_o and in the direction of X_u, therefore take the form: $\overline{X_oX_r}$.

Drawing the rays from to a single static point provides an ownship-centric view. This reveals the nature of the bearings relative to ownship as the target potentially manoeuvrers around ownship.

To represent rays from an ownship centric perspective, we pick an arbitrary point of the screen to render all rays from, say: $X_c = [c_x , c_y]$. The rays represented from an ownship-centric perspective require the unit vector relative to the arbitrary point, being the sum of the origin X_c and unit vector as $X_{rc} = X_c + X_u$. Ownship-centric rays originating at X_c and in the direction of X_u, therefore take the form: $\overline{X_oX_{rc}}$. The different perspectives, world-centric and ownship-centric, prompt different interpretations of the data and so reveal, or rule out, potential solutions in the problem space. The concept of rendering the same bearing data in world-centric and ownship-centric view is demonstrated in the next set of diagrams.

Figure 3 is an example scenario where the target is passing in front of ownship. It is assumed both vessels are moving at a constant velocity, and both paths begin and finish at the same time.

Figure 4 is an illustration of the bearings received from scenario *i* rendered from a world-centric perspective. As we can see, there are multiple overlap of the bearings, and the visualisation somewhat complicates a somewhat simple scenario, which may result in a misinterpretation by the operator.

Figure 5 illustrates the bearing data of scenario in Figure 3 visualized from an ownship-centric perspective. This perspective presents a much more clearer picture of the data to the operator, and therefore is more likely to lead to an accurate solution being identified.

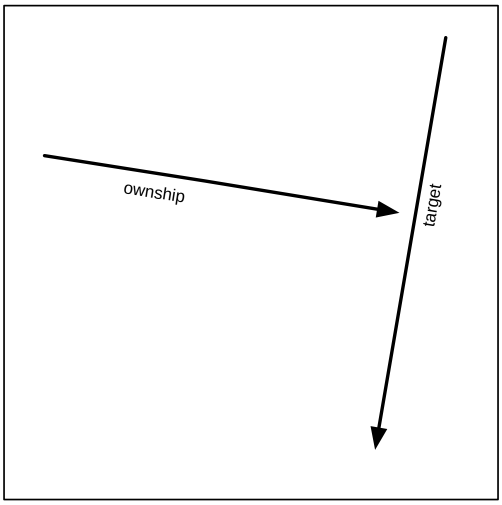

Figure 3: Simple scenario

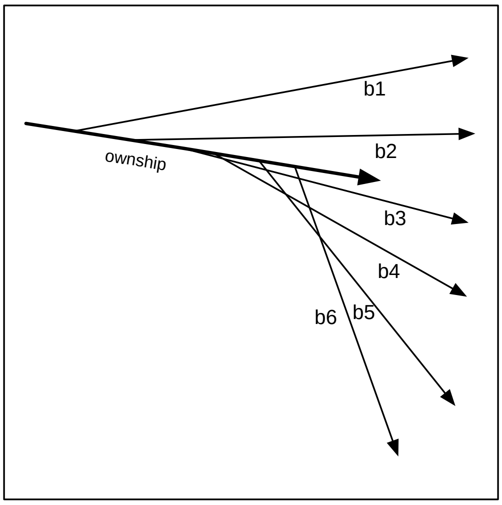

Figure 4: World-centric bearing visualisation

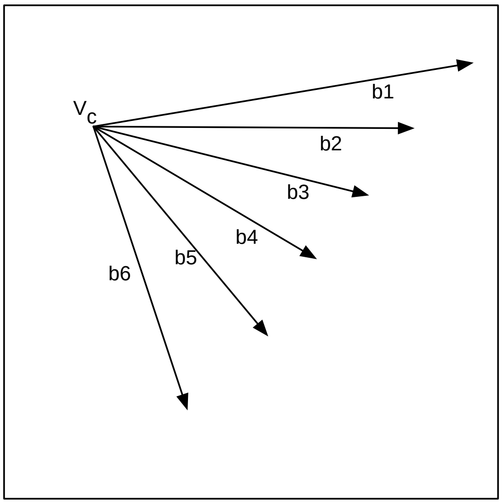

Figure 5: Scenario i from an ownship-centric perspective

Either of the two perspectives are not intended to be used exclusively, but instead both are intended to compliment each other; their full potential is exposed when the operator can use both visualisations in conjunction. To that end, we have provided in our visualisation the ability to transition between the two perspectives.

Animation is used to preserve context when transitioning between either the world-centric or ownship-centric view of the data. The origins of the bearings make an animated transition between the two states, and operator solutions too are transitioned. An operator can view a potential solution under one perspective, transition to the other perspective and see the solutions from the other perspective. These transitions between the ownship-centric and world-centric view of the bearings not only reveals other potential solutions the operator may not have been aware of, but also highlights erroneous or unlikely solutions.

3.3 Interactions

The objective of TMA visualisation is to identify potential solutions in the problem space. Identification of solutions is executed in a standard GUI point-and-click fashion. A solution, essentially being a piecewise path that passes through all the bearings, can be plotted out on the visualisations through mouse interactions.

3.4 Brushing

Brushing is a classic interaction technique, first defined by Becker and Cleveland (Becker and Cleveland, 1987), which we have explored in the investigation of TMA visualisation. In the TMA visualisations the operator manipulates the focus of the brush with the mouse. The brush can be used to highlight the individual bearings in a cluster revealing detail that is otherwise not obvious in the cluster itself, as depicted in the left panel of Figure 7.

The focus of the brush also effects the representation of ownship's path. As each bearing was taken at a particular point in time, the focus of the brush can be specify a particular time t. Taking a function $f(x)$ that gives a point along ownship at time x in the scenario, we can draw ownship path, up until point $f(t)$, fully opaque, beyond $f(t)$ drawn semi-opaque. By brushing over the clustered bearings the ownship path will highlight to indicate point in time at which the bearing was taken. This focus occurs in real-time and allows an operator to discern where ownship was at a particular bearing while still representing all the data.

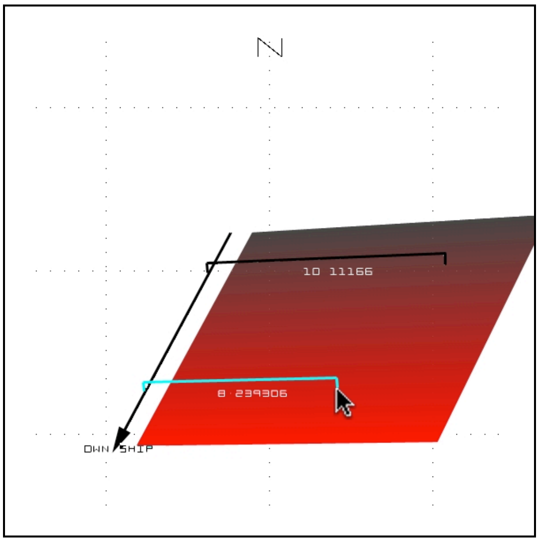

Figure 6: Brush labelling

We also apply Becker & Cleveland's concept of labelling. By this method the brush is used to reveal further data in the bearings not normally presented. This additional information can include the bearing data, in degrees or radians, and, more usefully, overlaying the distance from the brush to the ownship, as in Figure 6. This can help the operators identify solutions that are based on additional information received from other sources, such as the periscope.

The brushing technique becomes more useful when several visualisations of the TMA are presented simultaneously in different panels, as shown in Figure 5. In this case, we could have both the world-centric and ownship-centric visualisations of the bearings visualised in different panels on the display. The active panel would be considered to have the brush within it. Brushing is then used to link the same bearings between the two disparate visualisations and, thusly, removes the limitations brought up by viewing either method singularly while maintaining an understanding of the relation between the two visualisations. Only the bearings visible in the currently active panel are visible in the other visualisations, and any of the highlighted bearings in the

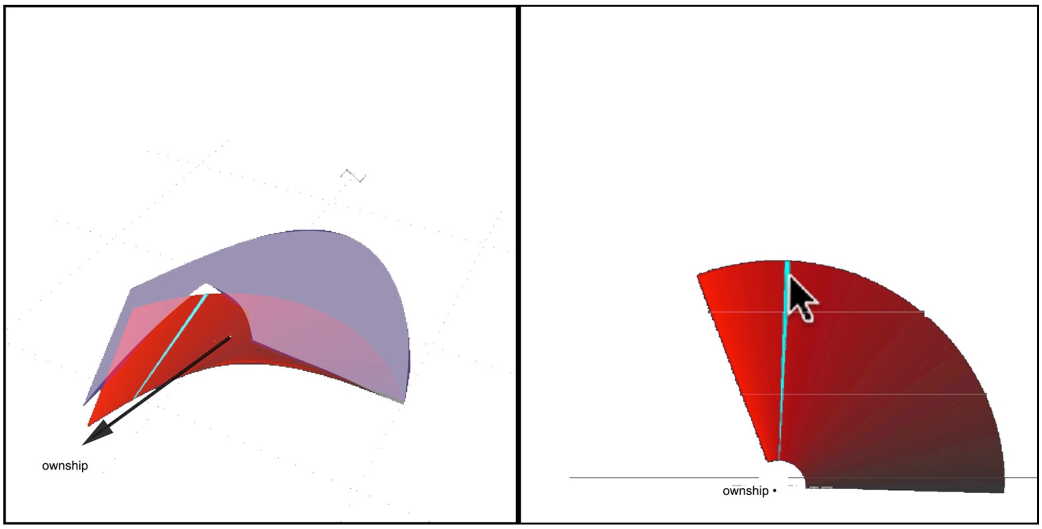

Figure 5: Multiple panels demonstrating brushing

active panel are also highlighted in the other panels. In Figure 5 the right panel contains the mouse and therefore is the active panel controlling the focus. As we can see, the mouse has brushed over a bearing sampled late in the scenario, and this bearing is highlighted accordingly. On the right visualisation, the same bearing is highlighted, thus allowing the operator to link the two bearings and thus recognize the relation between the two visualisations.

3.5 Expanding the bearings

As part of the visualisations we explored the potential of using three dimensions. Three-dimensional visualisations have the ability expand the volume of data presented, as well as influencing the interpretation of that data.

When viewing a large set of the bearing data involved in TMA, there can be several situations where this bearing data overlaps in the visualisation. This can lead to the occlusion of chunks of the bearings that can hinder the identification of solutions, or at worse can result in erroneous solutions being identified. The first three-dimensional technique we investigated involved using the third-dimension to alleviate the problem of data overlap. So far we have discussed visualising the bearings as either rays or clusters on the XY plane of the display. Using the third-dimension, the rays are drawn against the Z-axis, such that as the time-stamp associated with each bearing grows, so too does the z-coordinates of the rays.

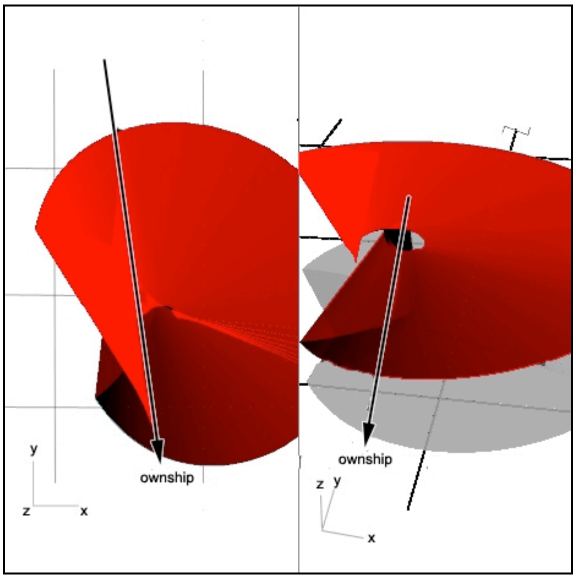

Figure 7: Time against the z-axis

Figure 7 illustrates the technique of using the z-axis of the three-dimensional visualisation to plot the time of the bearings. The left side of the figure represents the two-dimensional visualisations. The overlaps in the data are not clear and could result in a misinterpretation by the operator. The right side of the figure depicts the three-dimensional visualisation where the bearings utilize the z-axis to represent time. The visualisation implements a shadow beneath the bearings as a multidimensional cue to aid the immersion of the visualisation (Hubona, Wheeler et al. 1999). The operator can control the scale of the bearings along the time axis through a GUI slider, with the slider set at 0 there is no use of the z-axis for time, and as the slider value grows so does the bearings against the z-axis.

It is with direct manipulation that this visualisation's worth becomes apparent. The operator, unsure of the overlaps in the bearings, can interact with the slider to increase the visualisation into the third-dimension, observe the overlap, and then collapse the visualisation back down two-dimensions, all the while never releasing the slider. This interaction is fluid and reduces cognitive leap required when the manipulations are not direct.

3.6 Graphing

When observing bearings to make a target estimate, often the operator is more concerned with *changes* in the target bearings as opposed to the bearings themselves. If there is no change in the bearings over a period of time, it can be deduced that the target is maintaining a constant course in relation to ownship. More importantly, if changes in the bearings are present, the operator may deduce the target is moving in relation to ownship or executing a manoeuvre around ownship. It is, therefore, desirable for the operator to recognise changes that occur in the bearings as much as recognising the bearings themselves. Through perceiving the associated *rate-of-change* in the bearings, cognitive load on the operator is potentially reduced and the operator may more readily recognize hazardous changes in the target bearings. To that extent, the research has investigated the visualisation of these changes alongside the other visualisations discussed already.

The graphing visualisation extends the visualisations, such as the clustering technique previously discussed, into three-dimensional space. The graphing visualisation augments the bearings with a graph of the bearing changes rendered above the bearings themselves. This graph depicts only the changes in the bearings, not the bearings themselves. This is an important distinction, as the bearings are already implied by the cluster below the graph or may even be implicitly drawn on the visualisation itself. Furthermore, it has been shown "extraneous information detracts from the impact of the graphic" (Tufte quoted in Levy et al. 1996), which would imply that visualising the changes in the bearings is preferable to visualising the same bearing data twice within the same visualisation.

We define a function, θ_t . to represent the bearing data sampled at *t*, a particular point in time. The derivative of the function, represented as θ_t' , is the change in bearings at any particular time t, and is written as $\theta_t' = \lim_{t \to a} \frac{\theta_t - \theta_a}{t - a}$

To accentuate the changes in the bearings, and to allow the operator to control the influence of the graph upon the visualisation, the bearing derivative is adjusted by a user definable variable $v : f(t) = v \bullet \theta_t'$. By adjusted the value of *v* through a GUI slider, the operator will change the relative scale of the graph.

The graph utilizes a technique of occluding certain aspects of visualised data based on rotation of the view. In the approach we have taken, the aspects of data are not occluded naturally by the geometry of the data itself as in Wright's research (1995). Instead the opacity of the graph is a function of the rotation of the visualisation. When viewed directly down the *Z*-axis at the *XY* plane the graph is completely transparent. As the user rotates the visualisations on the *X* or *Y*-axis the graph becomes opaque and reveals itself. While this is a less natural interaction, the graph is more readily visible than the first approach and has more visual weight.

The graph is useful in cases where the operator needs to determine a great rate of change in the bearings. There are several situations in which a great rate of change in the bearings will occur, including: if ownship is manoeuvring, if the target is manoeuvring, or if the target approaches ownship at a great speed.

Figure 8 shows an erroneous solution decided by an operator. From this visual the solution could be considered a fair assessment. To be sure, the operator could reveal the graph visualisation by “tilting” the view. From the graph of bearing changes (Figure 9), it is obvious now to the operator that the bearings make a major change halfway through the sampling, as the graph makes a steep incline. In fact, the rate-of-change is seen to be growing up until the last bearing sample. This would suggest to the operator that a far more drastic solution is probable, such that the target begins to approach ownship at a rapid speed. From this the operator can adjust the target course to the more accurately match the data, as depicted in

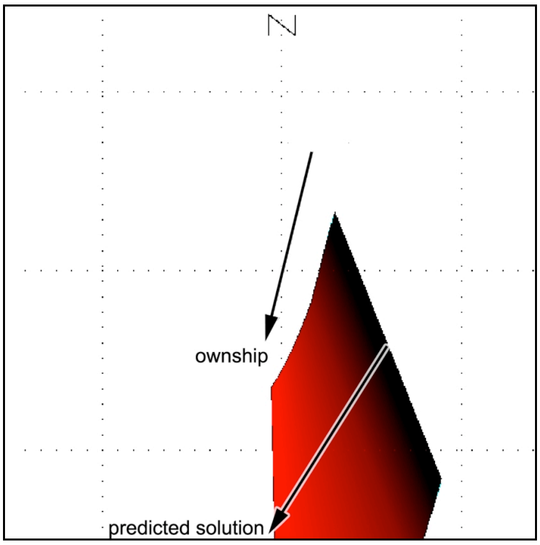

Figure 8: A scenario with an erroneous solution

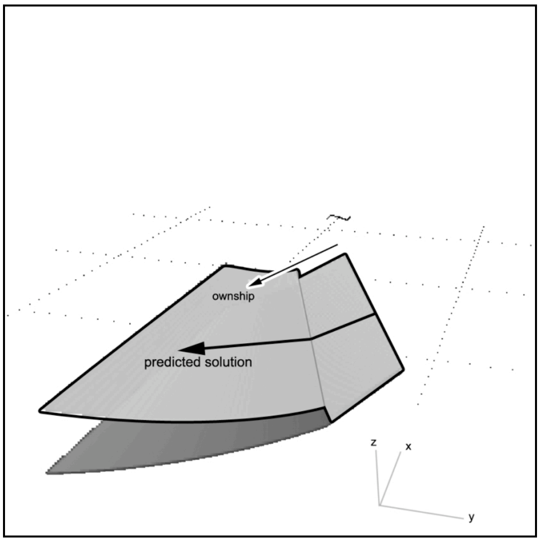

Figure 9: A corrected solution

When exploring virtual and augmented reality interaction utilities, such as public domain toolkit ARToolkit (Kato and Billinghurst 1999), the occlusion of the graphing data becomes a natural operation. As in the case of ARToolkit, an operator holds a tangible marker which, when rotated, controls the orientation of the visualisation itself. This interaction is interesting, as it somewhat reflects the action of real world model designer to tilt their head to see various aspects of a model (*The Case for Headspace*, 1999); in this case, an operator "tilts their head" to focus on different aspect of the visualisation.

3.7 Animation

Animation is an important technique when applied to TMA visualisation that encourages different interpretations of the bearing data and helps operators maintain context. Since the bearing data of TMA is taken in discreet time measurements it lends itself well to some of the visualisation concepts and issues raised several papers (Wright, 1995 and Nakakoji et al. 2001).

We have used animation as a technique for an operator to autonomously play through the bearings over a period of time. We represent the progress of the animation on a conventional GUI slider bar, where the slider thumb shows the operator the current progress and may be used to control the current frame and let the operator repeat sections of the animation.

So far, the visualisations we have discussed involved representing a large set of the bearings in a single, static frame. While displaying all the bearings in one visualisation is semantically equivalent to animation of the bearings, being able to view the visualisation using time as a dimension lends itself a vastly different perception of the data. A previous study (Nakakoji et al. 2001) has shown that animation lends itself well to many aspects of data exploration, of which particular to TMA is forecasting, filtering, and interpreting.

Forecasting: Forecasting is the prediction of the progression of data based on passed patterns. The operator can, for example, observe through the animation that the bearings are changing in a cyclic fashion and forecast the bearings to repeat another cycle.

Interpretation: Since bearings are related to the movement of a target, and with movement being a function of time, the fact that animation is also essentially a function of time may somewhat help the interpretation of the bearings.

The visualisation also implements Nakakoji's concepts of "after-feel" and "fore-thought" (Nakakoji et al., 2001); concepts that represent the immediate past and future state of the visualized data surrounding the focus of the animation. These help in maintaining context, as a small set of the past and future bearings are rendered in less detail around the focus in time; where less detail is represented as greater opacity. With after-feel and fore-thought the animation visualisation has a greater cognitive appeal since the operator can place the current frame of the animation in context. The operator also has control over these aspects through GUI sliders in the visualisation interface. The operator has control over the animation, over the focus in time and the relative speed of the animation.

4 VISUALISATION TESTBED

A testbed tool has been developed as a common platform to explore and evaluate the various visualisations operating under a variety of scenarios. The objective of the testbed is two-fold – to enable the uncomplicated creation of TMA scenarios and to facilitate rapid prototyping and evaluation of visualisations. The testbed is a graphical user interface (GUI) based tool built using a high-level object-oriented language and OpenGL, a high-level 3D graphics API from Silicon Graphics (OpenGL 2004), were chosen as a suitable platform for the visualisation prototyping due to the rapid prototyping capability and cross-platform nature of the solution.

The term *scenario* is used to refer to a discreet sampling of manoeuvres of ownship and a single target, and it was important that the visualisations be able to run under many different scenarios to ascertain their relative strengths and weaknesses. These user-definable scenarios are comprised of two paths, an ownship path and a target path. These paths are modelled in two-dimensions and are control point based. A path may have multiple control points, and each piece of the path, referred to in naval terms as a leg, may have a variable length.

From the scenerios, the testbed generates the bearing data needed to render any specific visualisations. As part of the visualisation testbed, the scenario editor allows the user to edit all aspects of the scenario. The scenario editor GUI replicates the functionality of most drawing packages, editing paths is done in a standard WYSIWYG fashion. Control points on the path can be easily added, multiple control points may be deleted and the whole path can be moved. The scenerio editor also allows the user to edit the knot speed of the path at a particular control point and calculates the acceleration of each piece of the path accordingly.

The testbed features a control panel, to allow various aspects of the visualisations to be affected by the user. These changes are reflected in the visualisations in real-time to aid user immersion. Each visualisation technique can be enabled, disabled and combined through options on the control panel.

We made the decision to include evaluation tools built into testbed itself; to allow a subject evaluating a visualisation to make annotations within the tool. Through either a tablet device or TabletPC, a user can directly annotate the on-screen visualisations. This approach enables evaluators to evaluate through on-screen textual annotations while they are interacting with the visualisation. Thus, the user is able to focus on the visualisation and the task of evaluation without having to remember their evaluations of earlier visualisations – essentially they can evaluate as they think in a natural way.

5 VISUALISATION EVALUATION

An expert review was conducted as part of this research. Expert reviews have been shown to be useful to evaluation and further research, as such a review comes from a position of knowledge (Booth 1989). The methodology entails reviews by experts in a related field to the problem and who are not directly involved in the project. As we was seeking qualitative responses from the expert review, it was conducted as an un-structured interview. Unstructured interviews take a free-form approach, allowing questions to be followed up by the interviewer and resulting in better *qualitative* feedback than a structured interview (Windschuttle and Elliot 1999).

The intention of the expert review conducted here was to receive feedback regarding the cognitive worth of the various visualisations from a "visualisation expert's" point of view. We conducted the review with a visualisation expert from Defence Science and Technology Organisation (DSTO), as a half-hour interview. Initially, the problem of TMA was presented to the expert, after which, the expert was guided through several of the visualisations with the intention to provide qualitative feedback. Each of the visualisation techniques were demonstrated under an ideal scenario, and again under a less than ideal scenario. The expert was then able to interact with the visualisations and provide feedback.

The expert review provided valuable feedback as to the cognitive worth of the visualisations, as well as indicating several possibilities for the future direction of the research. The general visualisation concepts such as clustering and brushing are agreeably beneficial in reducing an operator's cognitive load. Being able to reveal the levels in the data through these methods give an operator a better understanding of the bearings without overloading the cognitive process.

The concept of ownship-centric and world-centric raised an important difference between though process of a naval-operator and visualisation-expert. The expert review resulted in the opinion that an ownship-centric perspective seemed the more natural option. Much TMA visualisation research approaches the problem from a world-centric perspective (Clements, Kusmik et al. 2003; Virginia Tech 2004), whereas an ownship-centric perspective is arguably more intuitive to the average human.

The use animation in the visualisations is compelling, and the cognitive worth to a user is immediately obvious. Through the animation visualisation, a user can far better understand the nature of the bearings, since "the human brain is set up to interpret motion". This motion reveals when the bearings occurred in a very natural manner and allows the user to build up a mental-map of the bearings. Furthermore, being able to selectively control and play back the animation is immensely useful to the user's cognition. The bearings are far easier to understand when played at a user-defined rate, as opposed to watching the animation occur in real-time. Further research could investigate maintaining the orientation of the view so that it follows the path as it animates.

Some questions were raised regarding the cognitive worth of the three-dimensional graphing visualisation. While the interaction with the visualisation of tilting the visualisation did not draw criticism, the graph visual itself did. It proved to be difficult to comprehend over the time of the review, as the graph is not visually distinct from the rest of the visualisation. The expert questioned whether the information portrayed in the three-dimensional graph could be more effectively portrayed using two-dimensional visualisation techniques. For example, could pseudocolour be used to portray the changes in bearings instead?

Plotting time upon the z-axis provided some very positive feedback. It was immediately obvious how the visualisation "worked" and provided comments such as "the use of three-dimensions here is extremely helpful in perceiving the data". The expanding and collapsing of the visualisation into the third-dimension does not require any major cognitive leap. Recognising overlaps in the bearings through this technique is intuitive, as bearings animate and reveal the information dynamically.

6 CONCLUSION

Target motion analysis visualisation is a vast problem. The immense amount of data involved, and the uncertainty of this data, can place a great deal of cognitive load on an operator trying to identify potential solutions in the problem space. While computers are essential in TMA, in part due to their sheer processing power, the final process of amalgamating the broad range of information and identifying a potential solution, requires human input in the loop.

The aim of the visualisations identified in this research is to leverage operator cognition, and so reduce the number of erroneous solutions while revealing solutions that may not have obvious otherwise. Each of the visualisations helps identify target solutions that the operator would have been otherwise unaware of, or at least had difficulty identifying. When compared to the past methods of TMA, these visualisations help reduce an operator's cognitive load through offloading mental computation to a visual model – allowing an operator to concentrate upon the task of solution identification.

A good visualisation will reveal to the user the broad overview down to the minute details. The clustering visualisation that has been discussed provides the operator with a broad overview of the bearing data, while still portraying the general nature of those bearings. Through the use of brushing, the operator may selectively reveal deeper levels of detail in the cluster. Through interaction, the operator selectively reduces the amount of data being visualised at any one time, therefore reducing the cognitive load place on the operator. Throughout the 3D research, we were careful to ensure the visualisations are applicable to the problem of TMA, and that have some cognitive worth to the operator. Using the z-axis to plot time and graphing changes in the bearings became solutions suited to brief viewing to improve situational awareness.

There is still a great amount of work to be done in the field of TMA visualisation. Despite the wide range of work done investigating the mathematical nature of the problem, the visualisation aspect of TMA seems to have been relatively neglected. The visualisations presented here have proven their cognitive worth originating from the literature. While perhaps not all the visualisations presented here will be viable options to be developed into a mainstream system, they do show the worth of apply visualisation theory to the problem. Identified some novel solutions that will be beneficial to a TMA operator.

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