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SEARCH-BASED REAL-TIME PREDICTION OF CAE SOLUTIONS

BY

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THESIS

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ABSTRACT

Flexible hoses and cables are important components in the construction of an automobile. When designing a vehicle, it is vital to know the shape that a flexible component will take between its two endpoints. Incorrect information regarding hose routings can lead to shortened component lifespans and even costly recalls.

Because of this, great lengths have been taken to predict the shape of flexible components. In the past computer simulations using mathematical models have been used to predict hose and cable routings. Over time, these models have made many strides in terms of accurately predicting flexible component shape. However, computer simulations of hoses and cables are extremely time consuming, often times taking several hours or days. A new method of predicting hose shapes is needed to dramatically reduce this time burden.

This thesis paper proposes the idea of “looking up” a solution. Rather than calculating a hose shape, a search-based approach would be used that relies on a large database of intelligently represented solutions. A large amount of processing, indexing, and optimizing would be done offline on a backend database so a solution can be quickly generated. This method is known as the Search-based Real-time Prediction of CAE solutions (SRPCS).

In this research real hose shapes were generated in a test rig and stored in a database. This database was then used to search for other flexible component shape solutions in a feasibility study. The authors of this paper found that the SRPCS method provided an accurate and very rapid solution of flexible components. We believe that the concept of search-based solutions has been proven out in this research. The potential of this method needs to be further explored, including areas outside of flexible components.

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CHAPTER 1 INTRODUCTION

Automobile design has become increasingly complex due to the growing number of interacting systems that have to be designed under a large number of constraints. Yet, Original Equipment Manufacturers (OEM's), such as Ford and General Motors (GM), are expected to produce a variety of quality products that cater to evolving customer preferences. Product Development Cycle (PDC) timeframes have shrunk to keep up with the faster pace. As a direct result, the penalty for errors in product design has increased. There is now, more than ever, a need for tools that can validate automotive designs early in the PDC with high accuracy.

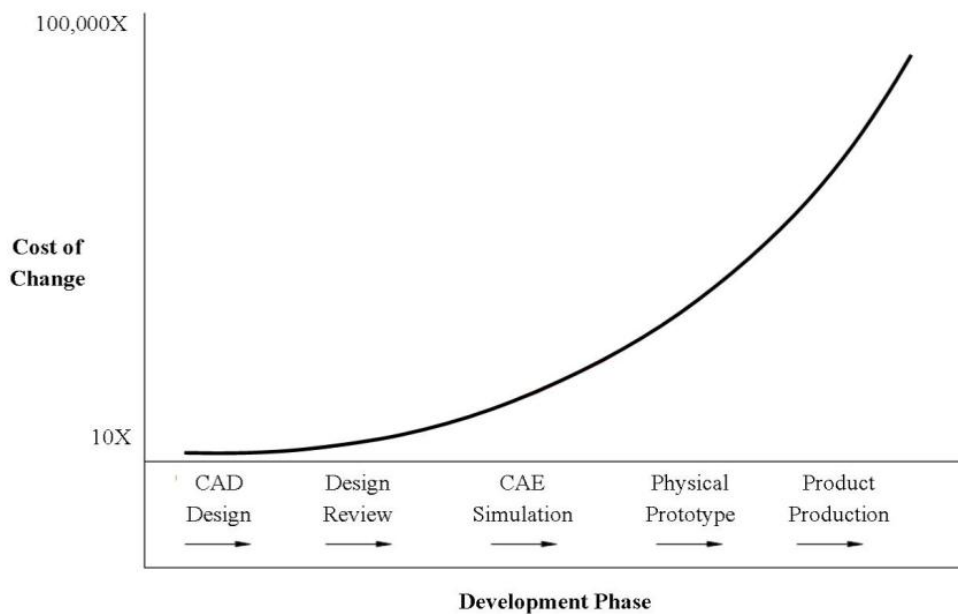


Figure 1: Schematic of Cost of Change Curve (taken from [1])

Figure 1, taken from [1] demonstrates this relationship between the cost of making a design change and the stage of the PDC. As the product development progresses (in this case, the x axis), the cost of making a change (the y axis) increases exponentially.

In order to overcome this problem, OEMs have increasingly focused on upfront design verification. Manufacturers have turned to Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE) tools. As a result they have significantly improved their virtual design capabilities and reduced the need for physical testing by using virtual verification techniques. As CAE techniques and hardware capabilities continuously improve, the ability of OEMs to analytically prove-out their designs also grows. However, while CAD tools have provided the

ability to do quick iterations and ‘what-if’ studies by changing the shape of product designs, the current CAE evaluation methods lag badly in speed, with a typical evaluation cycle taking at least an order of magnitude of time longer than the shape change.

In this project, we focus on *shape prediction*, or the calculation of deformed shape of physical objects that are subject to various loads and boundary conditions. In particular, we address the shape change of flexible components, such as wiring harnesses and brake hoses, whose large deformations are often impossible to predict accurately, even with the traditional CAE methods. Indeed, structural analysis (of which we have chosen shape prediction as the target for this phase-I project) is the single largest (at 30%) purpose for which CAE software are used, followed by 20% for fluid flow analysis.

A myriad of rigid-body parts have been researched in the past with the intent of reducing the number of design errors, or at least identifying errors early in the PDC. In this thesis, we focus exclusively on the design of flexible components, i.e., components which change shape as a part of their design intent. Their importance to the automotive design process is outlined in the following section.

1.1 Importance of Flexible Components to the Automotive Industry

Flexible components can be categorized as parts that change shape as part of their design intent. More specifically, hoses are used to transport fluids for a variety of applications. Examples include brake hoses, fuel lines, formed radiator hoses, CV joint boots, and stabilizer bars. Multiple electrical wires can be combined together as flexible cables, which behave in a similar manner to hoses. One of the most important aspects of flexible hoses and cables is the shape they will take under different conditions, also called routing. Routing can be defined as the path a flexible component takes between two endpoints.

Unlike other rigid components, flexible components must have the ability to offer consistent performance while withstanding large deformations [2]. These hoses and cables must also deflect in ways that result in favorable geometric conditions. For example, a brake hose that deforms between the vehicle frame and suspension, may rub against another rigid component, causing the hose to fail much sooner than desired. This is a very serious problem facing the automotive industry. We have been told that in 2005, nearly 2.5 million vehicles were recalled due to interferences between brake hoses and other under-the-hood and suspension components.

Thus, accurately predicting the routing of flexible components is essential to the continued improvement of automobile design.

Unlike other rigid components that stay close to their nominal design shape when installed and in-use, flexible components change shape drastically. For example, a brake hose attached to the brake caliper changes shape every time the wheel assembly moves up and down, or turns. The deformed shape of flexible components is a critical element in the assessment of its functional performance and effectiveness. This flexible shape presents a serious challenge to the traditional CAD design that implicitly assumes rigid geometries.

Three standard approaches are currently used for predicting the shape of automotive components: Computer Aided Design (CAD), Computer Aided Engineering (CAE), and Physical Prototyping. These are not mutually exclusive, as they are often used in conjunction with one another.

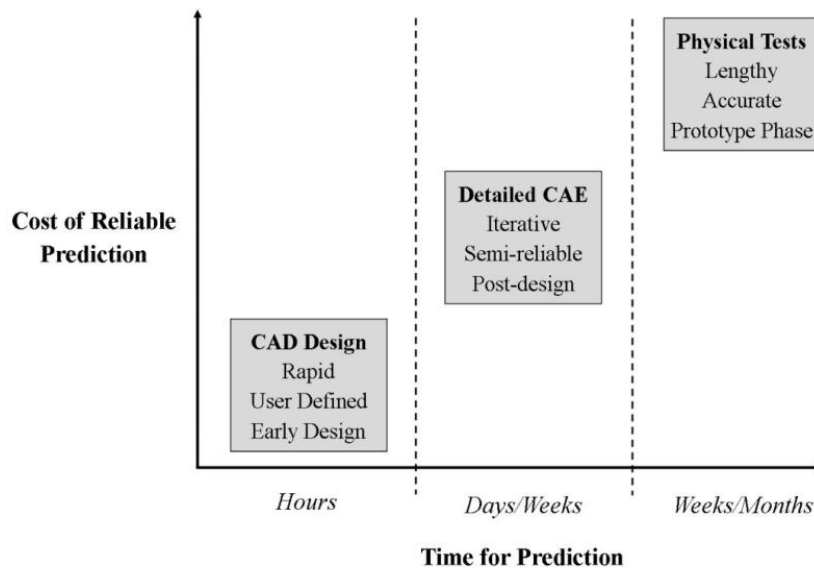


Figure 2: Methods of Flexible Hose Shape Prediction

Figure 2 illustrates the space of standard approaches used to predict the shape of a flexible component within their abilities to meet the requirements of time and cost of reliable prediction. In the progression towards virtual product creation, significant mismatches become apparent. While a CAD-based geometry design can be completed in a matter of minutes, the corresponding CAE analysis typically takes several days to complete. In a real-life benchmarking test at Ford Motor Company, as communicated to the authors, the analysis of the motion of a front suspension assembly, using rigid multi-body analysis was completed in 18

minutes, whereas the analysis of a brake hose that is attached to the wheel in the suspension assembly took 4.5 days to complete. Since CAD design progression cannot be idled waiting for CAE feedback of the performance of brake hoses, the designers usually proceed with a best-guess, experience-based or arbitrary estimation of the shape of the brake hose, i.e., the shape is user-defined. Physical verification, i.e., bench testing of the vehicle prototype has also been used regularly to evaluate the design signed off by CAD group without any analysis. However, such evaluation during the prototyping phase, although accurate, is invariably too late and could lead to enormous costs of design changes. It is also not in sync with the increasing emphasis that the industry lays on virtual prototyping to be available earlier in the PDC.

The three aforementioned approaches are further explained in the next section.

1.2 Approaches for Predicting Flexible Component Shapes

1.2.1 Computer Aided Design

CAD packages, such as Pro/Engineer, SolidWorks, and CATIA, have made it possible to capture the shape of automobile components in a virtual environment. Using these softwares, an engineer can design and assemble every car component, and observe how each interacts with each other. In the automotive industry, a large percentage of designs are rigid body components, including the body, dashboard, seats, etc. Many components are produced directly from the CAD model.

Flexible components can also be designed in a virtual environment. Many CAD software packages allow an engineer to route hoses and cables in dedicated routing applications. For example, Pro/Engineer and SolidWorks both have separate routing applications (Piping/Cabling and Routing, respectively) where hoses and cables can be modeled and assembled alongside rigid bodies. However, it is much more difficult to properly capture the shape of flexible components. Typically, hose and cable routings are “drawn” by a user, rather than by applied forces and moments. Thus, when compared with rigid body object modeling, the virtual environment design of hoses and cables provides low geometric accuracy, i.e., higher cost of reliable prediction.

Despite the low reliability, the CAD method for prediction flexible component shape remains very popular. For one, CAD-based methods are quick to create the initial designs. CAD is also quick in the way it provides instant feedback. A hose shape appears nearly immediately

after it is defined. Second, the cost of changing a design in CAD is low. During the early design phase, the only cost associated with modifying a flexible component is the time needed for redesign, virtually. In addition, the impact of changing a design is lower (as compared to other methods that occur later in the PDC).

1.2.2 Computer Aided Engineering

CAE is a broad term for the use of computer software in engineering-related tasks. We will limit the definition to the use of computer software for product analysis. Even through the economic downturn of 2008, the CAE market grew by 4.9% to \$2.8 billion, highlighting its ever-increasing value. Structural analysis, which includes shape predictions of deformed objects is the largest application of CAE software [3]. Some of the most widely used CAE solvers include ABAQUS, NASTRAN, and ANSYS. CAE provides shape predictions through mathematical simulation methods. These include, but are not limited to, Virtual Reality (VR) environments [4], Finite Elements (FE) [5], spring-mass models [6], rigid body chains [7], and flexible beam elements [8]. These methods have proven to be relatively quick and accurate for predicting the deformed shape of rigid components. Recent research has also demonstrated that CAE methods can simulate the shape change of flexible components. However, their expanded use in the automotive industry is limited by their high cost, need for experienced operators, and extremely long calculation times.

In industry, CAE is often conducted by a specialized division or a completely different company, where the analysis can be carried out by trained professionals. These skilled technicians are able to set up flexible component shape prediction problems. However, it may take anywhere from a few hours to several weeks to obtain results (Figure 2). CAE simulations demand large amounts of computing power. Running the simulations can be time intensive, especially for highly elastic components with large deflections, such as hoses and cables. In one example at Ford Motor Company, the motion of an entire front suspension assembly was simulated using rigid multi-body analysis in 18 minutes. But, the analysis of a single brake hose attached to the wheel in the suspension assembly took 4.5 days. Most companies cannot afford to leave design projects lay dormant for this amount of time while waiting for CAE results to return. Because of this time delay, engineers often move on in the PDC before results are obtained, usually using a best-guess, experience-based, or arbitrary estimation, hoping no issues

are found [9]. If there are issues brought out by CAE simulations, the cost of a design change is higher at this stage of the PDC than at the CAD stage. Engineers must adjust their designs and the CAD models. The CAE simulations (which are slow) may need to be run all over again.

Even if CAE results are quickly returned, some engineers still hold an inherent skepticism of the method [10] [11]. CAE simulations involve highly technical numerical techniques, including geometrical simplification, meshing, boundary condition and load setup, and conversion of solutions. Most designers are not trained in these techniques and thus, may not trust the findings. There may also be low confidence in the results because CAE is often handled in an outside division either within or outside of a company. Thus there can be a skepticism that the technicians may have set up the simulation with the wrong boundary conditions or under unfounded assumptions. For these reasons, some design teams skip flexible component CAE simulations and instead expect to test them directly using physical prototyping.

1.2.3 Physical Prototyping

Despite the advancements made in CAD and CAE technology, auto manufactures often use physical prototyping as an important step in design validation. This is usually carried out at the end of the PDC, right before ramping up to large scale production [1]. Usually at a dedicated test facility, a prototype car is built from the ground up under careful scrutiny while assembly issues are recorded. The solid components are first assembled. Test engineers will connect the hoses and cables to their endpoints and observe their routing. There may be interference positions or “rub” points, where the hoses or cables collide with each other or with other solid components. When this occurs, the test engineer will often fabricate a different length of hose, re-attach it to the prototype, and observe if the problem is fixed. This process may have to be iterated many times to obtain a suitable hose [12].

One disadvantage of physical prototyping is the high cost of conduction the tests and changes to the design, if required. Business units are often charged for time used in a test facility. Also, prototype components are often expensive because every assembly part is needed, but only in low quantities. Secondly, physical prototyping is time consuming [12]. Because the prototype is often being built for the first time, the assembly process can be very slow. Also, simply setting up the test area to prototype can take a substantial portion of testing. Because test facilities are often very busy, test engineers are often limited to a set schedule of a few days or weeks to

complete their analysis. If several issues arise which demands a longer period of testing, additional time may not be granted. Lastly, prototyping takes place at the end of the PDC, often on the verge of high scale production. Thus the cost associated with making a change is very high. If a large number of issues have arisen that require redesigning, production delays will result, which causes enormous expenses. Also, time must be spent going back and updating the designs, which may lead to other costly changes [2].

Even with the aforementioned disadvantages, physical prototyping remains the industry norm [12]. The main advantage to physical prototype is the ability to validate the cables and hoses in the same domain in which it will be used. As long as the production vehicle is assembled in the same manner as the test facility, the prototype verification is perfectly accurate. Assembling hoses and cables in the physical domain provides many benefits that are not feasible in the virtual domain, such as the ability to observe de facto properties. This includes things like ease of assembly/disassembly and maneuverability.

We have presented the three methods traditionally used to predict the routing of flexible components. However, each approach contains glaring issues. The goal of this thesis is to present a new approach to facilitate the shape prediction of flexible components. The next section presents the problem and overall approach

1.3 Thesis Problem and Overall Approach

Instead of the traditional three methods, we propose using a search-based approach for predicting the shape of flexible components. Such an approach would draw off of a large database of accepted hose shapes gained through physical testing. This ‘legacy-knowledge’ of known hose/cable shape problems and solutions can be stored on a backend server. When a flexible component problem is presented, our system will gather a large number of known solutions similar to the queried problem, and then interpolate a solution from the matches. Years ago this method would have seemed infeasible. But recent advances in software technologies, such as multi-core computing, XML, relational databases, web-services, visualization, and collaboration make the method very promising. This approach would be ‘Google-like,’ as a large amount of processing, indexing, and optimizing would be performed offline on the backend database, producing a solution in a timely manner. This new method is called the **Search-based Real-time Prediction of CAE Solutions (SRPCS)**.

Thus, the fundamental question that we are trying to answer through this project is: *Can a search-based approach be used to reliably predict the shape of a flexible component?* To this end, our overall approach consists of the following steps:

1. Hierarchical representation of the shape deformation problem, such that it captures the decomposition of a problem into sub-problems.
2. Matching query problem to known previously solved problems in the database.
3. Composing the overall solution (shape) from solutions of similar problems from the database.

In order to evaluate the proposed approach, physical testing will be carried out on flexible components to build a database of known shapes. Each shape will be based upon variables that are oftentimes relevant in an automobile such as: flexible component geometry and Boundary Condition (BC) locations. We will then apply the SRPCS approach, attempting to manually solve shape prediction problems.

In order to evaluate the proposed approach, physical testing was carried out on flexible components to build a database of known shapes. We will then apply the SRPCS approach and manually evaluate the correctness of the results.

1.4 Organization of the Thesis

The structure of this thesis document is presented as follows. In Chapter 2 we give an overview of the current CAE methods used to predict flexible component shape. Chapter 3 explains the new prediction method we are proposing. The experimental procedures and results are detailed in Chapter 4. We apply the SRPCS process in Chapter 5. We offer some concluding remarks regarding our contributions and future work in Chapter 6.

CHAPTER 2 LITERATURE REVIEW

As mentioned in Section 1.2.2, the area with the most promise to increase the speed and accuracy of flexible component shape predictions is Computer Aided Engineering. The following is an explanation of CAE methods that have been used by other researchers to predict the shape of flexible hoses and cables.

2.1 Current CAE Methods Used to Predict Flexible Hose Shapes

Several methods have been used to predict the shape of flexible components. However, these consist entirely of computer simulations based upon detailed mathematical models. As previously mentioned, these methods have proven to be too large of a time burden to be effectively used in industry. That is why the authors suggest “looking up” the solution rather than calculating it. After an extensive search, we have not found other researchers who have used this method. Thus there is no published material from which to refer. However, we will offer a short review of the mathematical models that have been used in the past to prediction hose shapes. Many of these methods overlap or can be used in conjunction with one another. We limit our literature study to the following broad approaches:

- Virtual Reality Environments
- Finite Element Analysis
- Model-based methods

2.1.1 Virtual Reality Environments

The limitations of CAD software modeling flexible elements have been previously mentioned. One Virtual Reality (VR) software, VRHose, was developed at Iowa State University to overcome this limitation [13]. VRHose was developed in conjunction with VRJuggler, a framework used to develop VR applications. This model was not based on material properties, but instead modeled as a spline. Continued research modeled hoses in VR as flexible beam elements using commercial softwares ADAMS preprocessor and Jack™ VR environment [2] [14]. The flexible beam element was set up using fixed attachment points with control points that could be modified. The VRHose program provided the shape prediction. It then imported the beam model into the Jack™ software and presented in CAD. This hose model was later validated by a real hose deflection in a single plane. However, the model could not account for twisting.

Other work done through commercial software is IDO, developed by ICIDO gmbh [15]. This software supports the design of flexible components. This software predicts hose shapes in VR through material properties, including density, modulus of elasticity, and Poisson's ratio. However, much of the shape in the IDO is defined by user interaction. Thus if a long section of hose is unrestrained, the software will not provide an accurate prediction of hose shape. No data exists which can validate the shapes predicted by this model.

In [4], Gousskov, Leon, and Mikchevitch describe the use of VR environments to simulate the Assembly/Disassembly (A/D) of flexible automotive parts. The flexible part is set up in VR through user-defined points. The hose prediction is given in real-time through Interactive Mechanical Models (IMM). The IMM supplies realistic forces and displacement estimations. The fact that the estimations are carried out in VR allow for visual evaluation of the A/D process.

2.1.2 *Finite Element Analysis*

Finite Element Analysis (FEA) is one of the most popular methods of analyzing the deformed shapes of solid components. The FEA process can be broken down into three stages: pre-processing, analysis, and post-processing [9]. To begin the preprocessing stage the boundary layer of 3D models are broken down into a system of points called nodes. The grid of nodes is called a mesh. In between each node, the mechanical and structural properties are stored into linear elements. The mesh works together as a large series of linear equations that are all related to each other by nodes that will have related displacements. Once this preprocessing stage is complete, loads are applied for the analysis. As forces and moments are applied to the mesh, the series of equations can be calculated, providing displacements at all the nodes. By using the correlations between force, displacement, Young's modulus, and such like, the stress across the 3D model can be presented to the design engineers; this is the final post-processing stage. The engineers will interpret these results and make design changes accordingly. Oftentimes, a mesh will contain hundreds if not thousands of nodes and elements. Thus it is easy to see why finite element calculations can be time consuming [5].

FEA is the primary computation model used in today's most popular CAE software packages (ABAQUS, NASTRAN, and ANSYS). However, most of these packages are not equipped to carry out FEA on models that contain large elastic displacements. Even if the packages can carry out the calculations, the added complexity of the calculations increases the

computation time exponentially. Therefore, FEA is not used extensively in industry for prediction hose shapes, though there are exceptions. Fuji Heavy Industries Ltd has used MARC, a commercial FEA software package for brake hose routing design. This method was evaluated by Kusunoki and Miyashita and reported to be useful [16]. However the deviation from real hose shapes was not made clear.

2.1.3 *Model-based Methods*

1) Flexible Beam Elements

A brake hose model was created by Sugiyama and Otaki by dividing it into particles and flexible beam elements [8]. “The shape of the hose was determined by solving the equations of static equilibrium resulting from the element forces on the particles” [2]. The initial conditions were the main drivers of the final hose shape. The main draw from Sugiyama and Otaki’s work was the ease of computation, leading to reduced calculation time for solving equations for static equilibrium [8].

As previously mentioned, Keil et al. created a flexible beam model in the VR environment ADAMS [12]. The “discrete flexible link” function of ADAMS was used to create massless beam elements between two user defined attachment points. Keil’s work was verified through physical testing of real hoses.

2) Spring Mass Models

Gregoire and Shomer attempt to predict hose shapes of one dimensional flexible parts through research at DaimlerChrysler. According to [6], a three dimensional part can be simplified by using the Cosserat model for rods. In this model, a hose is modeled along its centerline. The remaining properties (cross section geometry, material properties) are integrated as being part of the centerline. The Cosserat model leads to a series of ordinary differential equations where forces and moments are coupled to positions and orientations.

Attempts by Gregoire and Shomer to solve the ODE’s were unsuccessful, due to difficulty in to determine appropriate initial conditions. To avoid these difficulties, the authors experimented with a spring-mass model, similar to what was used in the past by researchers at DaimlerChrysler [17]. Instead of a continuous centerline, the hose was modeled as a series of mass points connected by linear and torsional springs along the centerline. The linear and

torsional springs provide the length and bending stiffness, respectively. The mass points store the remaining properties of the hose. The spring-mass model was applied in the VR software *veo*. Results were compared with real hose data and shown to be accurate.

3) Rigid Body Chains

In [7] a flexible elements are modeled by a series of cylinder segments of equal size. Each segment is connected by a ball joint. At each ball joint there is a modeled spiral spring giving the hose its shape. This is unlike the spring-mass models, where the linear and torsional springs create the connection between mass points. The hose routing in the rigid body chain method is determined by minimizing the potential energy between the end conditions. The results of this research yielded fast, but rough hose shapes.

2.2 Limitations of Current Approach

Currently, the greatest hindrance to using CAE for predicting hose shapes is the amount of time it takes to model the problem and generate a solution. Automobile manufacturers need to be able to generate results with the accuracy of CAE at the speed of CAD. Once this is achieved, CAD and CAE can be iterated synchronously, offering the incredible potential for better quality and faster design verification. There are currently many researchers working diligently at improving the speed and accuracy of the computational models used by CAE software. However, significant strides need to be made before flexible components can be predicted by CAE at the speed of CAD.

In this thesis, we propose an entirely new way, i.e., using a look-up based method, of predicting the shape of flexible components. Several researchers have used search based solution methods in areas outside of the shape prediction field. In Appendix A.1, we provide a summary of the other domains where the search based method has been successfully employed. Also, in Appendix A.2, we offer reasoning for the method of storage for a flexible component database.

CHAPTER 3 THE SRPCS APPROACH

3.1 Overview of the SRPCS Approach

The SRPCS approach for predicting the shape of flexible components is shown in Figure 3. The overall goal of the SRPCS is to look up a solution rather than calculate one. The following sections are a step by step walkthrough of the steps in the SRPCS solution process shown in Figure 3.

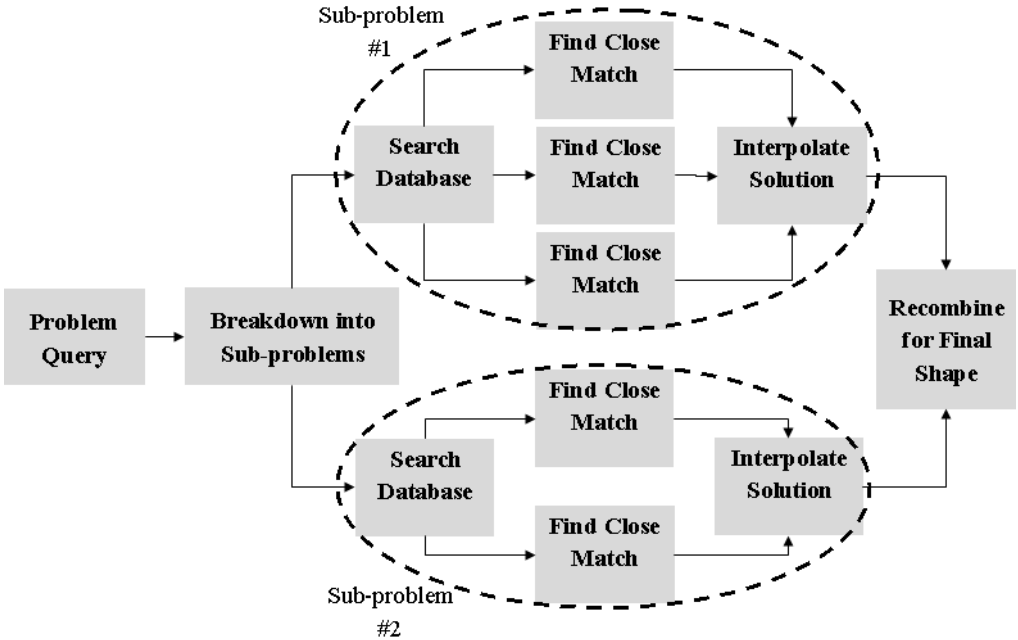


Figure 3: The SRPCS Approach

3.1.1 Problem Query

Shape prediction problems for flexible components will normally come with information that is known and information that needs to be determined. In the domain of vehicle design and assembly, the engineer knows the locations of where the flexible component needs to begin and end. This is known as the endpoint or boundary conditions. It is normal to know the type of flexible component needed for the queried connection. This will also include the properties of the hose or cable, such as length, diameter, material properties, etc. Given this information, main unknown to be determined is the path that the component will take between the two boundary conditions. This is the queried problem to be solved.

3.1.2 Breakdown into Sub-problems

Some CAE methods will attempt to solve the shape problem as a whole. We believe that it would be better to solve the problem query through a series of sub-problems. The solutions to each of these sub-problems can be combined at the very end to obtain the solution to the overall problem. By taking this approach, we are able to break one complicated flexible component problem into several problems with simple solutions. Figure 4 shows how a particular shape prediction problem could be broken down into three sub-problems. The question then presents itself with how to section a hose or cable problem in a consistent manner among various queries.

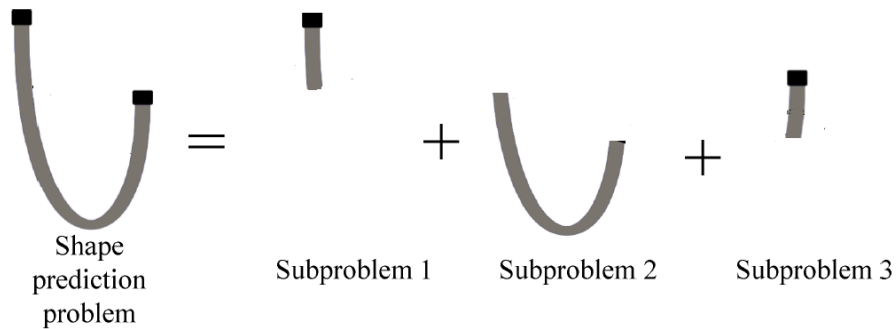


Figure 4: Sectioning a Shape Prediction Problem in to Sub-problems

A list of criteria is needed to break a problem into small enough sub-problems in which each sub-problem has a valid shape prediction. We propose a heuristics approach to intelligently section the geometry using a set of atomicity criteria. For the purposes of this research, atomicity criteria is defined where the flexible component is sectioned by a series of requirements that are either fully satisfied or not satisfied at all, i.e. no judgment calls need to be made whether to section the geometry or not. We discuss the list of atomicity criteria for our experiment in Section 3.3.

3.1.3 Search Database and Find Closest Matches

Once the problem has been queried and broken down into sub-problems, we go to the database for solutions. This database consists of intelligently represented solutions to known flexible component problems. Given the boundary conditions and component properties of each sub-problem, the SRPCS process will comb through the database, looking for close matches to the given problem.

There are two tools needed for finding close matches. The first required tool is a list of similarity measures. This list defines the likeness of the sub-problem and the flexible component

shapes. The similarity measures used in this thesis work is seen in Section 3.4. As with the atomicity criteria, the list of similarity measures may evolve as this research is continued. It is unlikely that a shape in the database will perfectly match all of the similarity criteria. Thus there is also a need for a tolerance level. The tolerance level sets how closely the shapes in the database must meet the similarity measures to the sub-problem to be considered a close match. With these two tools, the SRPCS will gather a set of closest matches to each sub-problem. Then the question arises of how to combine those matches into a solution.

3.1.4 Interpolate a Solution and Recombine

When the closest matches are found, they will be assigned an aggregation measure based on how closely the candidate matches the similarity measures of the queried sub-problem. For each sub-problem, the SRPCS process will take the closest matches and interpolate a solution from them. This is done by taking a weighted average of the matches and combining them to form the solution. The matches which have higher aggregation measures will be weighted higher in the combination process than those matches which did not as closely match the sub-problem.

After each sub-problem solution is generated, they are combined to form the final shape. The resultant shape is the predicted shape of the query problem.

3.2 Component Properties to Store in the Database

The knowledge database will consist of known flexible component shapes. Simply storing the component routing is not enough information to fully capture the problem. Other properties must be stored alongside the shape. However, flexible hoses and cables have a myriad of properties that could be stored. The question becomes which properties are worth storing. A literature review was carried out on four research publications where these properties had to be taken into account [2] [4] [6] [18]. We used these four papers, along with our understanding of the needs of the SRPCS to develop a list of properties worth including in our database. Table 1 shows the resulting ‘core’ properties we believe should be stored along with the component routing.

Table 1: Core Properties

Core Properties	Variable
Flex Component Length	L
Area Moment of Inertia	I
Young's Modulus	E
Lateral Spacing	y
Longitudinal Spacing	x
Attachment Angle	θ

Many of these properties can be measured before gathering hose shapes. The hoses were cut to specified lengths. The inner and outer diameter of the hose was measured with a caliper. The inner and outer diameter is used to calculate the area moment of inertia. Each hose was also weighed. Knowing the length, inner and outer diameters, and weight of the hose provided us a complete definition of the geometric and mass properties of the hoses.

It was also important to know the component's material properties. Most important in this would be its resistance to bending, which is best defined by the elastic (or Young's) modulus. The elastic modulus is measured by taking the slope of the material's stress-strain curve.

The remaining core properties are set up while running the experiments. Figure 5 displays the parameters lateral spacing, longitudinal spacing, and attachment angle. The lateral and longitudinal spacing are defined by the horizontal and vertical distance between the endpoints in our experiment. The angle the endpoints form with each other is the attachment angle. For the purposes of this research, we only consider attachment angles of 0, 90, and 180 degrees. A more thorough explanation of these properties and the methods used for measuring them can be found in Appendix A.3.

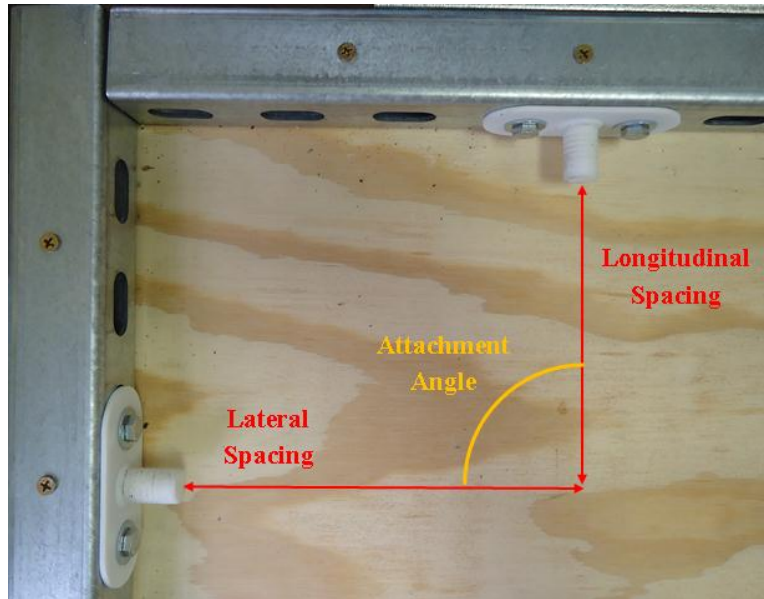


Figure 5: Boundary Condition Properties

3.3 Atomicity Criteria

We decided to use a heuristics approach to create a list of criteria used to take a complicated flexible component problem with an unknown solution, and ‘section’ it into smaller problems with known solutions. This list is known as the atomicity criteria. We believe that our set of atomicity criteria will produce flexible component routings of an optimal size for storing and searching. We call this optimally sized shape the atomic shape.

In order to demonstrate, we take a complicated flexible component shape and apply the atomicity criteria to break it down into atomic shapes. In essence, the component routing is ‘cut up’ into smaller routings with known solutions, as mentioned previously in Section 3.1.2. It should be noted that cutting a flexible component into smaller sections always occurs on a plane that is parallel to the component cross section at the point of the cut.

3.3.1 *Identifying the Endpoints and Travel Path*

- a. The two endpoints are identified and “cut”. The endpoints are the two ends of the flexible component.
- b. Determine the starting point of travel.
 - The order for choosing the side from which the starting point will be: North, West, South, and East.
 - If there are two endpoints on the same side, start with the one that is closer to the North-West intersection.
- c. The travel path is defined as being from the starting point to the other endpoint.

3.3.2 *Sectioning Flexible Component*

- a. From the starting point travel along the hose path, constantly checking to see if the following atomicity criteria are met (the atomicity criteria are listed in order of importance). If so, cut the component. A section is defined as the hose geometry from the current cut to the previous cut.
 - Cut component at any discontinuity
 - Cut component at a change in the material
 - Cut component at a change in the cross section
 - Cut component if it bends one direction < 90 degrees relative to the most recent cut then bends back the other direction to form a 0 degree angle relative to the most recent cut.
 - If the component bends at an angle of 90 degrees relative to the most recent cut:
 - Continue traveling along component routing. If the routing continues to bend to form a 180 degree angle relative to the most recent section and crosses a line perpendicular to the most recent section at that 180 degree angle, cut there.
 - If not, cut at the point where the component bends at a 90 degree angle.

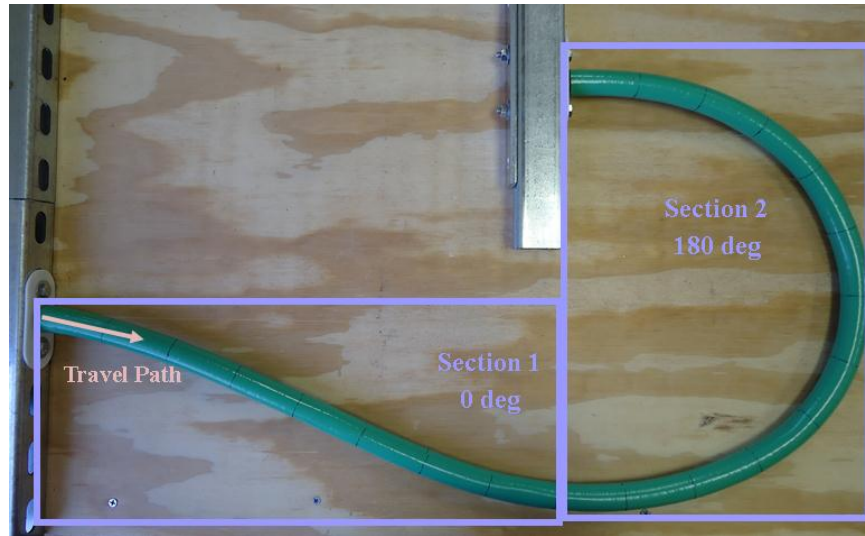


Figure 6: Hose Decomposition Example

Figure 6 demonstrates the process of applying our atomicity criteria to cut up the hose. In this case, the more complicated shape was broken down into two smaller shapes. We can generate a solution for each of the smaller shapes, where it would have been difficult to solve for the complete shape. In Chapter 5 we demonstrate the effectiveness of this approach.

As this research matures, the list of atomicity criteria will grow and refine. However, we believe that the information presented here is the foundation from which to build going forward.

3.4 Similarity Measures

As Section 3.1.3 points out a set of criteria is needed to define similarity between the problem and the database of flexible shapes. As we search the database, we look for atomic shapes that match the list of criteria within the set tolerances (rarely will an atomic shape perfectly match the problem). A set of closest matches is then gathered to form the solution to each sub-problem. The number of closest matches will depend on the search criteria and the associated tolerances. Thus, it is important to use the right set of criteria to search the database. The following criteria are explained in their order of importance.

When trying to find the appropriate similar hose or cable shape, the first thing to look for is the bend case. As shown in our atomicity criteria, we define the flexible components as 0, 90, or 180 degree bend cases. In this similarity measure, there is no tolerance. Solutions to 0, 90, and 180 degree bend problems must be found from the 0, 90, and 180 degree bend databases, respectively. The next two similarity measures go hand in hand. One is the elastic modulus; the

other is the area moment of inertia. Both are useful for determining component's resistance to bending. As mentioned previously, the elastic modulus describes the material properties while the area moment of inertia describes the cross sectional geometry.

Two ratios were recognized as being most helpful when determining similarity between the problem and the atomic shape database. We call the first, the Endpoint Spacing Ratio (ESR). This defines the relationship between the two lateral and longitudinal spacing of the endpoints. Figure 7 displays the three bend cases and different values associated with each one. The ESR would be defined as the A/B ratio. Note that the 180 degree bend cases do not have an ESR.

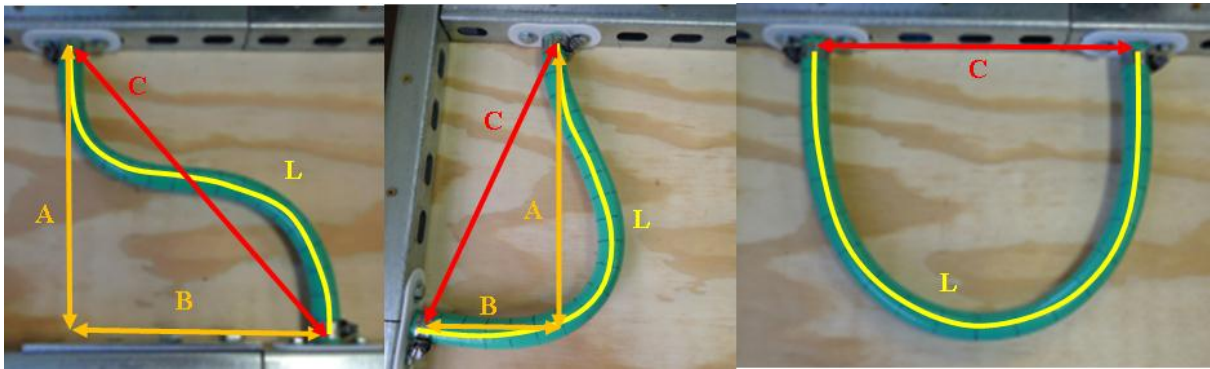


Figure 7: Diagram for Showing Similarity Ratios

The ESR alone is not enough to determine similarity among similar bend cases. Shapes with identical ESR's can follow different routings. The second ratio that can make the necessary distinction is the Length Spacing Ratio (LSR). This ratio is defined as C/L , referencing Figure 7. Practically, the LSR states how much the flexible component deviates from a straight line drawn between the boundary conditions.

Just using the aforementioned metrics allows for the possibility of several matching shapes where the hoses are all of different lengths. Therefore, the length of the flexible component should be another measure taken into account when gathering close matching flexible components. In review, the following similarity measures were used to match hose shapes.

- 1) Degree bend case (0, 90, or 180 deg)
- 2) Elastic modulus
- 3) Area moment of inertia
- 4) Endpoint Spacing Ratio (ESR)
- 5) Length Spacing Ratio (LSR)
- 6) Length of the hose

It is no coincidence that the list of similarity measures is analogous to the core properties. What is important in defining a flexible component shape is also important for comparisons. This criterion is also applied to a shape matching problem in Chapter 5. As further research is carried out, the list of similarity measures will be expanded and refined. However, we believe that the ones mentioned in this report will remain applicable.

CHAPTER 4 EXPERIMENTAL SETUP AND RESULTS

4.1 Existing Data

As previously mentioned the SRPCS method requires a database of known flexible component shapes. The quickest and easiest method of building this database would be to use hose and cable shapes already generated by the automotive industry and other researchers. Keil and Rodriguez attempted this approach, but “countless calls to manufacturers and members of the hydraulic hose committee of SAE have convinced the authors that flexural data for hoses does not exist. Thus, anyone wanting such data for modeling must generate it” [12]. Our own correspondence with Ford Motor Company confirmed this statement. There is not a database of known flexible component shapes currently available. It was then determined that we must create our own shapes to build our database. Thus it was required that we create a test rig where we could generate this data.

4.2 Construction of the Experimental Setup

4.2.1 Test Materials

Figure 8 displays the materials used to assemble the experimental setup. The test rig was constructed on a plywood base. Unistrut C-channels were permanently secured along the North and West sides to a plywood base creating a fixed border on those respective edges. The boundary conditions were made in the Ford Rapid Prototyping lab on the Formiga P 100 Selective Laser Sintering System. These boundary conditions were made to fit on the Unistrut channels. Figure 8 also displays the mounting hardware used when setting up the tests. Two types of water hoses were used for this test. These are less expensive and more readily available than hydraulic or brake hoses. However, the construction of a water hose is similar to those used in the automotive industry. Three lengths of hose were used: 400 mm, 600 mm, and 1200 mm. The hoses were divided into 21 sections, spaced evenly across the straight-line length of the hose. At each section, the hose was marked.



Figure 8: Supplies for Test Rig (l to r): Unistrut C-channel, Boundary Conditions, Hoses, Attachment Hardware

4.2.2 Test Rig Setup

Figure 9 can be referenced for the setup of the test rig. As mentioned previously the North and West edges are fixed in place. The South and East edges were set in place using the unfixed Unistrut channels and mounting hardware. This configuration was varied with each test for the desired lateral and longitudinal spacing. The boundary conditions were attached to the channel to create the desired endpoint conditions. One boundary condition piece was always fixed to the North face of the test rig, known as the origin. If both boundary conditions were attached to the North face, the endpoint closer to the North and West intersection was the origin.

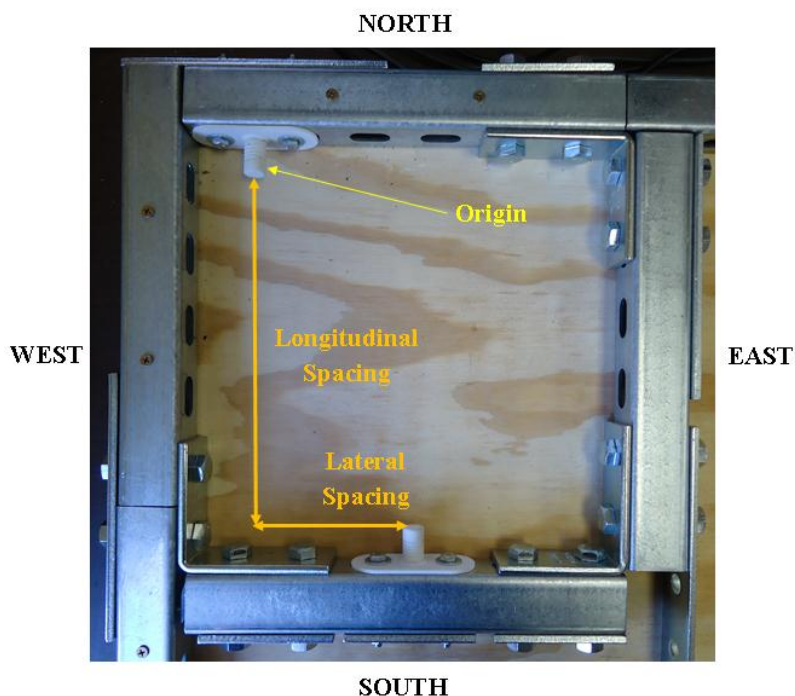


Figure 9: Test Rig with Boundary Conditions in Place

One end of a hose was slid onto the origin boundary condition. We secured the hose with a clamp. Next, the opposite end of the hose was attached to the second boundary condition and secured with a hose clamp. It is important to refrain from applying torsion forces while securing the hose. Hoses are stored reeled up on a cylindrical drum or wound in a loop for compact storage. This gives the hoses a rest curvature as shown in Figure 8. In each test the hose was oriented so that the rest curvature did not significantly affect the two dimensional flexible component routing. Once in place the flexible component will have a routing between the boundary conditions. Figure 10 displays an example shape.



Figure 10: Test Rig with Hose Attached (Shape #6)

4.3 Data Collection

The hose shape was measured as an array of points. Using a metric tape measure, we measured the space from the North and West faces to each of the 21 hose markings. The distance between the West face and hose marks is the i value; the j value is the distance between the marks and the North face.

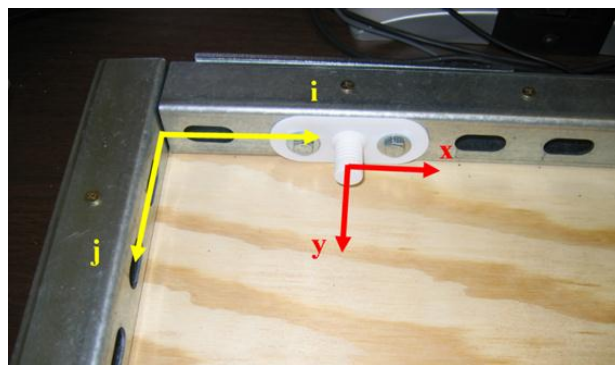


Figure 11: Boundary Condition

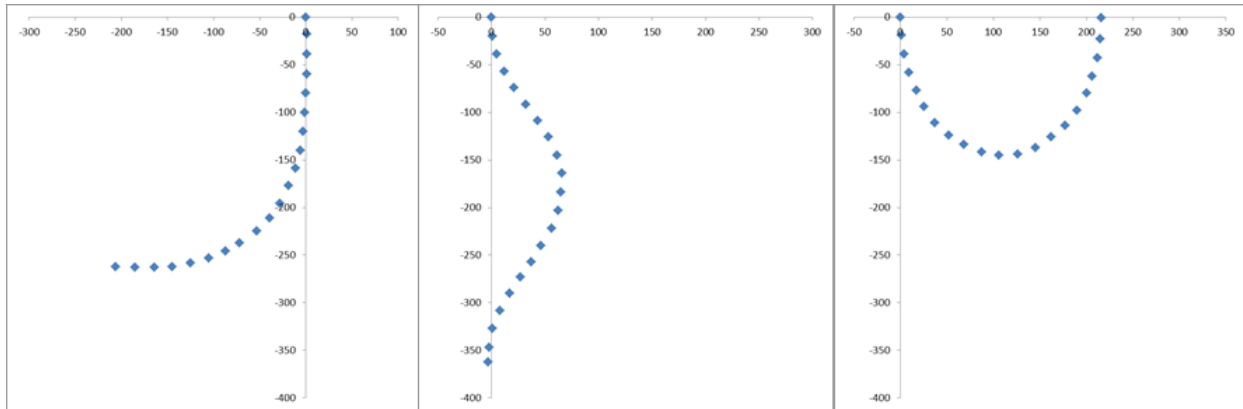


Figure 12: Examples of Stored Hose Shapes (left to right: 0 deg, 90 deg, 180 deg)

At this point the array of coordinate measurements is relative to the test rig faces. Using the i-j coordinates of the origin boundary condition, we shifted all points so that the array was relative to the origin (the first boundary condition). Figure 11 shows the shift from i-j coordinates to x-y coordinates. The x-y coordinates were stored in Microsoft Excel with the core properties according the procedures laid out in Appendix A.4. Each x-y array was also plotted in graph form to provide a visual representation.

4.4 Types of Data Collected

Over a period of several weeks, various hose shapes were gathered and stored. The following is a listing of the types of hose shapes with which we currently are working.

4.4.1 Atomic Shapes

In the context of this research, the term atomic refers to something that cannot be dissected into smaller parts. Therefore, an atomic shape is a one that will not be broken down into a set of more standard shapes.

We defined atomic shapes as one of three categories. According to our criteria these shapes cannot be broken down into smaller shapes. These criteria will be discussed further later on. They are defined by the angle orientation of one boundary condition relative to the other. The three orientations are 0, 90, and 180 degrees. Figure 13 displays examples of each orientation of atomic shape.



Figure 13: Examples of Atomic Shapes (left to right: 0 deg, 90 deg, 180 deg)

These atomic shapes are the building blocks of the knowledge database. Only the 400 mm and 600 mm hoses were used to gather atomic shapes. These are the shapes that will be searched, interpolated, and combined to solve flexible shape problems.

4.4.2 *Non-Atomic Shapes*

Non-atomic shapes are defined as any shape that falls outside the three categories mentioned previously. Figure 14 displays an example of a Non-atomic shape. The 1200 mm hose was mainly used to gather these hose shapes. We gathered a few examples of non-atomic hose shapes in order to test the usability of the atomic shapes. The non-atomic hose shapes were stored in a separate database. We later attempted to match the routing of the non-atomic shape through a combination of atomic shapes. This was done as a ‘proof of concept,’ showing that one can break down a complicated flexible component problem into smaller solvable parts. The results are discussed later.

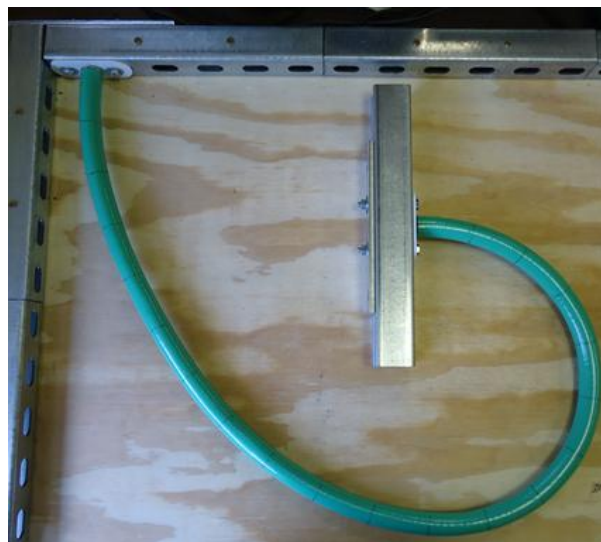


Figure 14: Example of Non-Atomic Flexible Component Shape

4.5 Limitations

To our knowledge we are the first researchers to attempt to build a database of flexible component data. Therefore, we enforced some limitations in order to simplify the construction of our test rig. First, it was decided that we would only look at hose shapes in a two dimensional plane. Second, the boundary conditions for the hose shapes were oriented only at 0, 90, 180, or 270 degrees. Both of these limitations allows us to simplify and speed up the process of gathering flexible component shapes. It also makes the database much easier to search and interpolate. Once our idea of searching for a solution is proven, the limitations can be removed and the research should go into more depth.

4.6 Experimental Results

4.6.1 Interpolating

We wanted to evaluate how well we could predict hose shapes using just the atomic cases we have. Using the stored hose shapes, we looked at group of three hose shapes where only one boundary condition was changed. The low and high sets of x-y coordinates were averaged. This was compared with the actual middle case routing. Red squares represent the actual middle case routing and the blue circles represent the average between the other two arrays.

For the cases shown, averaging the x-y coordinates proved reasonably accurate, as seen in Figure 15 through Figure 19. In Figure 15 through Figure 17 both boundary conditions were varied. In the case of a 90 degree bend, the average is moderately accurate in prediction the actual hose shape. However, in the 0 degree bend the inaccuracies are magnified.

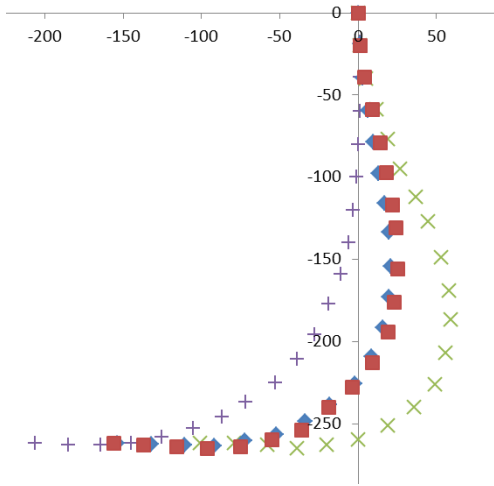


Figure 15: Test Case 1

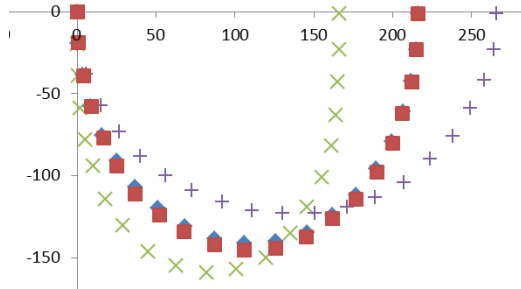


Figure 16: Test Case 3

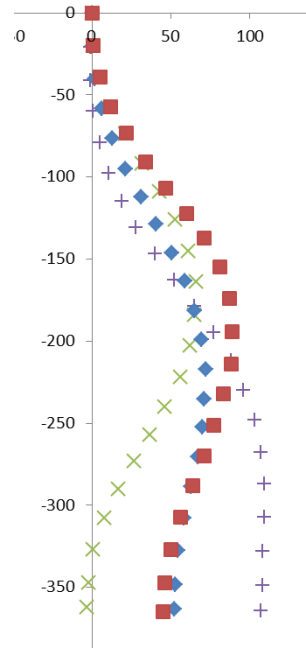


Figure 17: Test Case 4

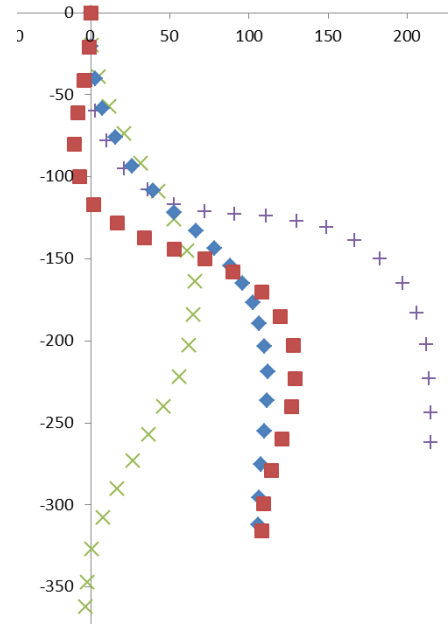


Figure 18: Test Case 15

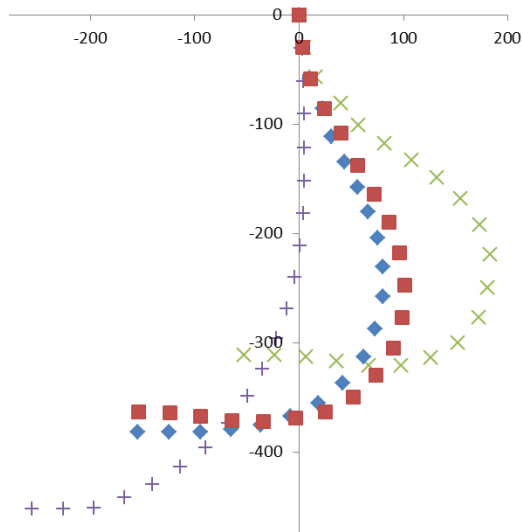


Figure 19: Test Case 16

4.6.2 Expand and Shrink

While building the database, it was observed that flexible components of differing lengths, but similar boundary conditions will often have similar routings. This led us to wonder if hose shapes can be scaled in size. This was done by comparing the hose shapes where the hose length was different. Two of the results are below in Figure 20 and Figure 21.

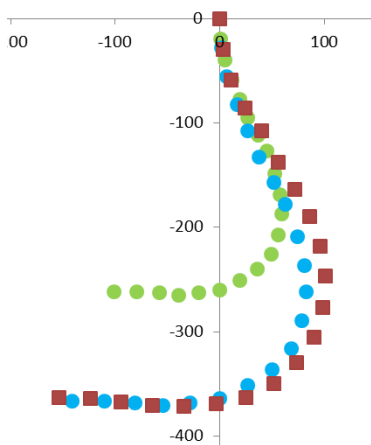


Figure 20: Shrink Expand Test 2

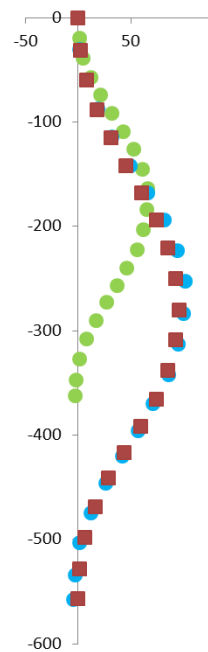


Figure 21: Shrink Expand Test 3

In the above figures, the green dots represent an actual routing from the 400 mm hose, while the blue dots represent the same routing expanded. The x-y array values were multiplied by a constant value to achieve this expansion. The red squares represent an actual routing from the 600 mm hose. It can be seen that the smaller length flexible component shape scales up to the shape from the larger hose well. This shows that hose shapes can be expanded or shrunk in order to match hose shapes.

4.6.3 Differing Shapes

When gathering hose shapes, we observed that some hoses can take two different shapes even under the same boundary conditions. This always occurred when gathering data for the 0 degree atomic shapes. This can be seen in Figure 22 and Figure 23. What determines the shape is how the hose is connected to the boundary conditions. We define this as two different configurations a flexible component can take under the same boundary conditions.

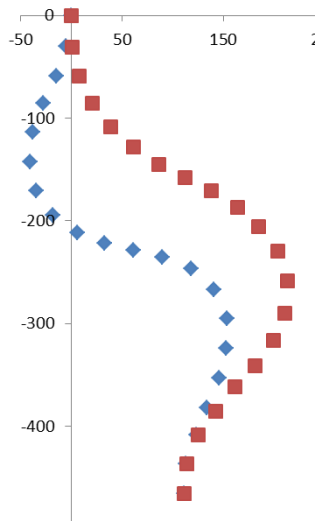


Figure 22: Shape 42

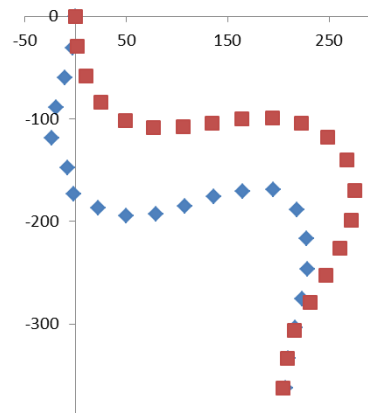


Figure 23: Shape 46

If the hose is hooked up in one method, the hose takes a symmetric configuration where the shape holds symmetry about a line running between the two boundary conditions. The hose can also take an asymmetric shape if held another way while attaching to the boundary condition. This raises the question about which hose shape to use when determining how to interpolate a solution. If one looks at Appendix A.5 it can be seen that in most cases, using the symmetric hose shape is a better predictor of other shapes. However, this is not always the case.

4.6.4 Deviation Ratio

The question arose of if the Length Spacing Ratio is an accurate representation of the amount of deviation of the flexible component routing. To answer this question, another metric was created, called the Deviation Ratio (DR). This ratio was used only on the atomic shapes. We first calculated the maximum amount the hose deviated from a straight line drawn between the boundary conditions. As shown in Figure 24, $x_1, y_1, x_2,$ and y_2 correspond to the location of the boundary conditions. The points x_0 and y_0 were varied to achieve the maximum d value. This provided a maximum deviation for each atomic shape.

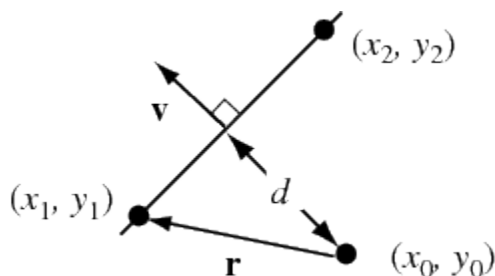


Figure 24: Distance of a Point to a Line

$$d = \frac{|(x_2 - x_1)(y_1 - y_0) - (x_1 - x_0)(y_2 - y_1)|}{\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}}$$

The longer hoses will naturally have higher deflections than the shorter hoses. To normalize this, the deviation ratio is defined as d/L , referencing Figure 7 and Figure 24. The DR was calculated for all the atomic hose shapes. Figure 25 displays the relationship between the LSR and DR for the entire atomic shape database.

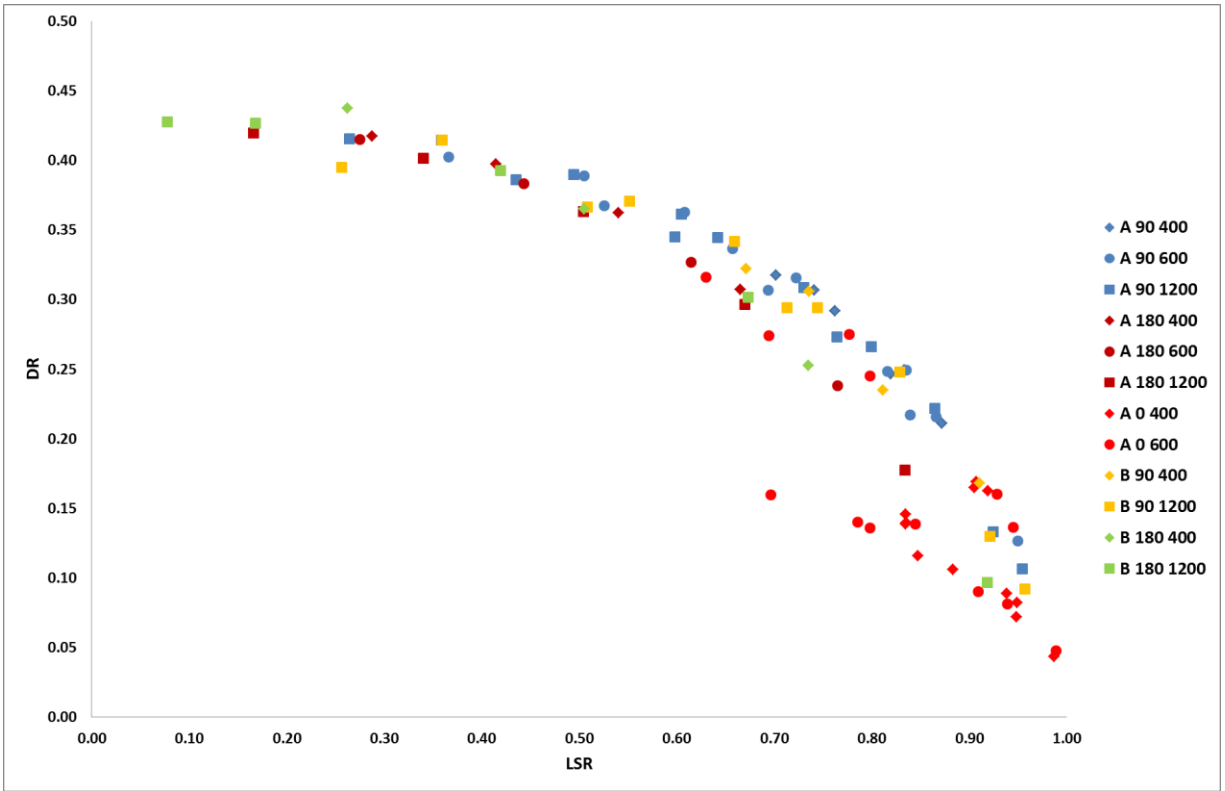


Figure 25: Comparison of DR to LSR for Atomic Shapes

We can see that overall there is a good correlation between the LSR and DR. This occurs regardless of the stiffness of the hose, orientation of the boundary conditions, and length of the hose. In the instance of the 0 degree bend cases, there is more variance in the correlation than the other cases. This can be attributed to the different hose shapes that were mentioned in Section 4.6.3.

The deviation of a flexible component can only be calculated if the shape is known. Thus it is not useful as a similarity measure, because in that case one of the shapes is unknown. Conversely, the LSR metric is known without viewing the component routing. But, because there is a good correlation between the LSR and DR, we can use the LSR to predict the amount a hose will bend out of line. Charts similar to what is shown in Figure 25 could prove to be useful to design engineers as a quick reference when modeling flexible components in CAD. The charts would provide a good estimation for a flexible component routing, even without an automated SRPCS system. Appendix A.6 shows the LSR-DR comparison in individual 0, 90, and 180 degree cases.

CHAPTER 5 THE SRPCS APPROACH APPLIED

When a flexible component shape problem is presented to the SRPCS, the database will need to be searched for a list of possible solutions. It is unlikely that an exact solution will exist in the database. Thus, the SRPCS must have the ability to search through the database, gather a list of solutions that closely match the problem, and interpolate a solution. In order to gather a list of closely matching solutions, a set of criteria is needed to define similarity between the problem and the database of flexible shapes.

As we search the database, we look for atomic shapes that match the list of criteria within the set tolerances (rarely will an atomic shape perfectly match the problem). A set of closest matches is then gathered to form the solution to each sub-problem. The number of closest matches will depend on the search criteria and the associated tolerances. Thus, it is important to use the right set of criteria to search the database.

We attempted to take the non-atomic hose shapes and match them with a combination of manipulated atomic shapes. This was a manual process that is to be automated with further research. We will present here an example of one non-atomic shape to illustrate the SRPCS approach used to search the atomic shape database and match the non-atomic routing. This example is also demonstrated in the excel document ‘Test - S1.’

We first selected a non-atomic flexible component shape to match. This is the queried problem. The non-atomic hose shape was plotted as an x-y array in excel. We then broke the shape down into sub-problems following the atomicity criteria mentioned in Section 3.3. Figure 26 shows how the non-atomic shape was sectioned as 90 and 180 degree bend cases.

Next, we begin the process of searching through the atomic shapes database using the similarity measures shown below. For this example, we will only demonstrate the searching process for the 90 degree bend sub-problem.

- 1) Degree bend case (0, 90, or 180 deg)
- 2) Elastic modulus
- 3) Area moment of inertia
- 4) Endpoint Spacing Ratio (ESR)
- 5) Length Spacing Ratio (LSR)
- 6) Length of the hose

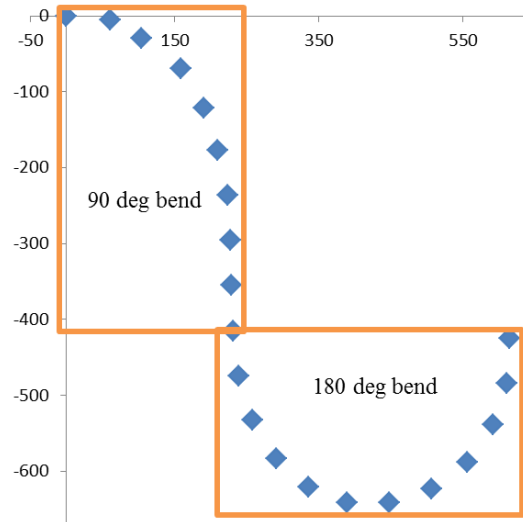


Figure 26: Sectioned Shape

The first step is limiting the search to only 90 degree bend cases. The second and third steps to searching the database are considering the elastic modulus and area moment of inertia. In this case, the non-atomic shape was taken using hose of type A. This limited our search to the shapes in the database of the same hose type. This means that there is perfect similarity with the elastic modulus and area moment of inertia.

The sub-problem bend case was 90 degrees. This limited our match search to the 90 degree bend atomic cases. The queried sub-problem had a hose length of ~538 mm, an ESR of ~1.8 and an LRS of ~1.1. We manually searched the databases for shapes with similar values for the ESR, LRS and hose length. The top three results we found are shown in Table 2. This table compares the sub-problem in bold with the closest matches.

Table 2: Close Matching Shapes

Shape	ESR	LSR	Length (mm)
Sub-problem	1.8	1.1	538
#3	1.7	1.3	400
#31	1.7	2.0	600
#32	1.8	1.2	600

Using the metrics given, Shape #32 was the best fit. The ESR, LSR, and hose length of the atomic shape is a close enough match to the shape to use without interpolating with another shape. Shape #32 is shown in Figure 27. If we were presented with a situation where a close

shape could not be found, we would interpolate between a case with higher and lower values of ESR, LSR, and hose length.

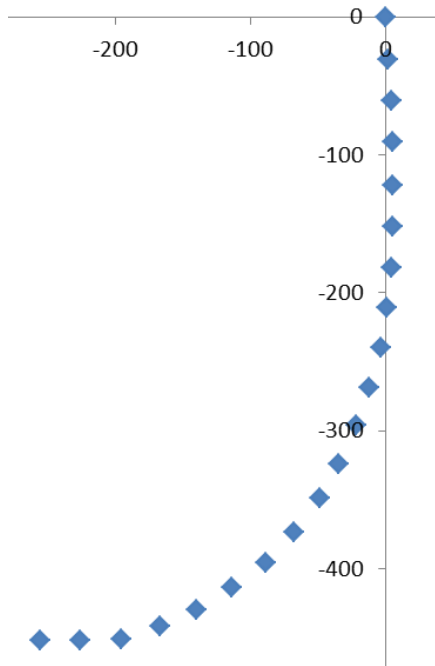


Figure 27: Shape #32

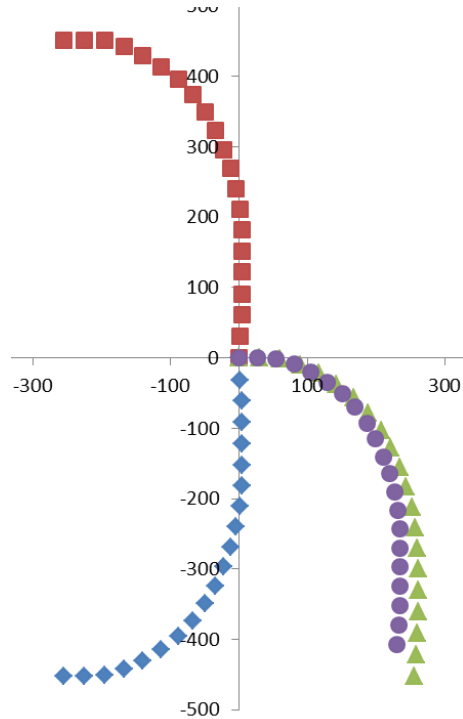


Figure 28: Progression of Shape #32

Although Shape #32 was a close match according to all the similarity measures, it still needed to be manipulated to get a good shape match with the queried sub-problem. Figure 28 shows the progression of manipulations Shape #32 went through to better match the sub-problem. Shape #32 in its tested form was in an undesirable orientation. Thus the x-y array was flipped on the Y axis (red dots) then shifted (green triangles). At this point, the shape was slightly larger than the sub-problem. To force a better match, the x-y array was shrunk by a constant value. The validity of this manipulation was shown in Section 4.6.2. The final shape (purple circles) is generated solution to the 90 degree sub-problem.

A similar process was used to generate a solution the 180 degree bend sub-problem. These two sub-problem solutions were then combined for a final shape. The matched case can be seen in Figure 29. The queried problem, which is the non-atomic shape, is shown in blue. The solution to the 90 degree sub-problem is in red and the 180 degree sub-problem is shown in orange. The accuracy in this instance is very high.

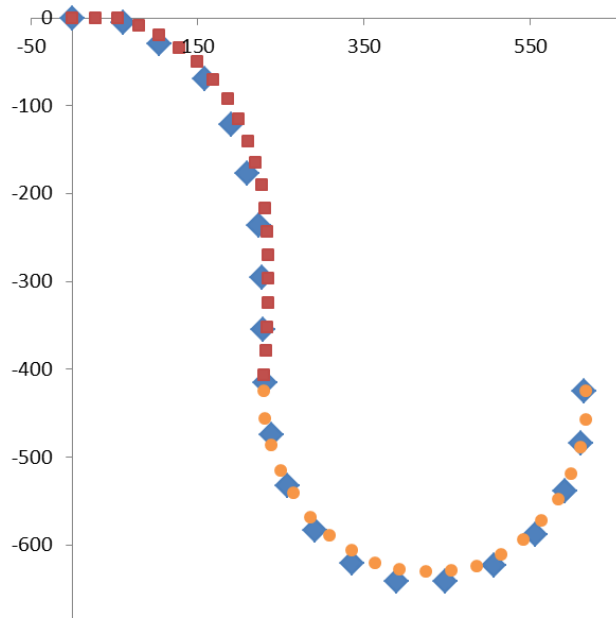


Figure 29: Non-Atomic Shape Matching

This is only one of several shape matching problems that was carried out on non-atomic flexible component shapes. Similar results occurred for the other shape matching problems which can be seen in Appendix A.7. We believe that this demonstrates that the SRPCS approach is a valid for predicting the shape of flexible components. This method should be further explored and refined, as it holds the possibility to be a great benefit to the automotive industry. Also, this solution procedure, whereby we break a complicated problem into smaller parts and solve those parts based on a database of prior knowledge, provides immense potential for areas of research outside of the automotive industry.

CHAPTER 6 CONCLUSION

6.1 Contributions

We are the first researchers to begin exploring the idea of using a searched-based approach to predicting flexible component shape. Because of this, we focused on the “proof of concept” for this thesis. The end goal of this thesis work was not to produce a fully automated predictor of flexible component shapes. Rather, the goal was to verify that the searched-based method is a worthwhile pursuit of predicting component routings. We believe that this thesis has shown that the searched-based method is worth pursuing further. We presented that the CAD, CAE, and Physical Prototyping methods of predicting flexible component shape each have significant downsides. The SRPCS method offers the possibility of accurate flexible component predictions which are generated quickly at an early phase in the design process.

We demonstrated our method for building a database of known hose shapes. At the end of my research, the database has over 70 cases of atomic shapes. We are the first research group to attempt this method, thus the experimental procedures for creating this database is useful to the automotive industry. We also give a list of core properties that should be stored with each shape in the database.

We showed our methods for using the database to predict non-atomic hose shapes. We first proved that atomic hose shapes can be interpolated and expanded/shrunk in the process of generating a solution. In order to properly divide more complicated hose problems into sub-problems, a decomposition process was laid out. This included a set of atomicity criteria for sectioning flexible component shapes.

We proposed a technique for searching the database to find a set of closest matches to the sub-problems. This involved the creation of similarity measures. The solutions to these sub-problems were then combined to form the overall solution. In the end we proved that a non-atomic flexible component shapes can be represented as a combination of atomic shapes.

The work regarding the Deviation Ratio was not directly part of the proposed solution process. However, the charts that were generated via the creation of the Deviation Ratio could prove very useful to automotive design engineers. They provide a quick reference guide to the shape of a hose under a set of boundary conditions.

6.2 Future Work

Although we have made several contributions to the research area of shape predictions of flexible components, there is still much work to be done. In the work that was done for this thesis, all flexible component shapes were limited to those in a two dimensional plane. Many automobile hose shapes can be approximated as a routing in a 2D space. However, a fully functioning SRPCS should be able to predict routings in the 3D world. In order to move this research from 2D to 3D, a new test rig will most likely need to be constructed. Also, the experimental procedures for capturing the flexible component shape will most likely differ.

In Section 3.1 we laid out the process by which a flexible component problem can be decomposed, the database searched, and a solution interpolated. However, this process was always carried out manually. To fully capture the usefulness of the SRPCS method, the solution process must be automated. This can be done in future work.

The main purpose of an automotive hose is to carry pressurized fluid from one location to another. When a hose becomes pressurized, it will often change shape due to the forces exerted by the compressed fluid. Due to time constraints, we did not pursue this aspect of the research. Pursuing this aspect would have required a more complicated experimental setup, whereby pressurized fluid would be pumped through the tested hoses. It would be useful to eventually integrate the effects of hoses under pressure within the SRPCS solution method. Building the new test rig will be the main challenge this pursuit. In Appendix A.8 we have written up a project proposal for the construction of a new test rig. This could possibly be used as an independent study, senior design project, or similar opportunity.

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APPENDIX

A.1 Knowledge-based methods

To our knowledge, the idea of “looking up” the shape of flexible components has not been pursued by other researchers. However, several other researchers have used a searched based solution method in areas outside of the shape prediction field. However, the solution method has never been applied to flexible components. Here we will provide a summary of other domains where the search based method has been successfully employed.

A.1.1 FE Analysis

An important component in the development of an automobile is the Body-in-White (BIW) design. BIW describes the structural body of a vehicle [9]. The main method of analyzing the structure of BIW designs is through Finite Element Analysis (FEA). As previously mentioned, the FEA process consists of three stages. Of those three stages, pre-processing (creating the mesh) is the most time consuming and labor intensive [19] [20] [21]. It also contains about 80% of the cost of the total analysis cost [22].

There are large similarities between BIW automobile designs. However, in many companies a new mesh is created for each analysis. Chapman and Pinfold [9] argue that large amounts of time could be saved by using an automated knowledge based approach. A database of existing FE models and meshes would exist as the knowledge base. The database could be searched for close matches to a new BIW structure to be analyzed. Close matches would be modified to suit the new analysis. This reduces the need to create entire new meshes. To test this idea, the authors created a mesh for a BIW structure. A “Deign Analysis Response Tool” (DART) graphical interface was developed which allowed an engineer to take the existing mesh and create a new BIW from a close match. The researchers found that a new, accurate mesh could be generated from a close match, saving several man days of work that would have been spent generating a new mesh from scratch.

The one area not addressed by this research was that of searching. A close match was given at the start, as opposed to being found in knowledge database. It was not published how efficiently a computer can comb through a database of mesh structures and gather a set of close matches. Also, Chapman and Pinfold do not break down the overall problem into sub-problems, as we do with the SRPCS. Solutions are generated at the highest problem level.

A.1.2 Product Design

In automotive production, large amounts of technical design expertise are created. However, it is difficult for other designers to reuse this knowledge because they do not know how to obtain it. Conventional CAD programs do not provide designers with the knowledge to develop good designs; they simply offer the tools for the engineer to create.

In [23], Wang *et al.* discuss and demonstrate how knowledge based engineering can be used in the design process, specifically in armored vehicle design. Legacy knowledge is stored in a database. When a designer inputs the requirements, goals, and overall idea of a design into the system, the database is searched for close matches. The closest matches are presented to the engineer so he/she can make reference to other designs that have been used in the past.

A.1.3 Engineering Changes

Manufacturers today are constantly trying to improve the quality and reduce the cost of their products on a rapid timetable. Engineering Changes (EC's) are made to provide incremental improvements to products. EC's must be evaluated to see if the improvement outweighs the associated burdens, such as time and cost. Many times, domain experts must decide if an engineering change should be accepted, evaluated further, or discarded based on their own expertise.

In [24], Mehta and Patil present the idea of using the knowledge-based approach to evaluate EC's. Similar to the solution method mentioned in the previous two sections past EC's can be stored in a database that can be searched for similarity. The legacy knowledge then aids the evaluation of a proposed EC.

Mehta and Patil address an issue that many other researchers in this field fail to mention. They note that determining similarity measures for searching a knowledge database is a large challenge. One must first determine a set of important properties of a proposed EC and use only those for retrieving matching past EC's. Some of these attributes have interdependencies with each other. Also, some attributes are discrete and others are continuous. These are a few of the challenges associated with database searching.

A.2 How to Store Flexible Component Shapes

As mentioned, the SRPCS process requires a database of flexible component shapes. The question arises of how to store the flexible component data. There are a myriad of methods that various researchers have used to store and search shapes for similarity. B-splines representations are often used. They are rich, but tedious to compare. On the other hand, histograms can be compared quickly. From a set of random points on the surface of the model, we shall use a shape function that computes the distance between two random points, since it has been found to be most robust and efficient for computing shape distributions and is invariant to rotation and translation. The shape distribution is given by the histogram that measures the frequency of occurrence of distances within a specified range of distance values.

Paper [25] discusses shape similarity searching for 2D drawings. One method “represents the shape of a 2D drawing from the statistics perspective as a distance distribution between two randomly sampled points.” This describes shape histograms.

Presentation [26] offered a comparison of feature based, graph based, and geometry based shape searching methods. Graph and geometry based methods are computation heavy, similar to what is used in FE software programs. The three feature based methods include, global features, spatial maps, and local features. The feature based method includes shape histograms. One limitation of feature based searching methods is that rotation is not recognized. This is a good thing for our purposes, because only one orientation of a flexible component shape is needed to be stored. Another limitation is that there is no relation between the features and parts of the object. This is acceptable because we only consider the singular shape. Table 3 displays a table comparing all the methods listed in [26]. Comparatively, shape histograms score high marks for their efficiency, discriminative power, and robustness. All three are very important to this project. For these reasons we recommend that the flexible component data be represented as shape histograms in the database.

Table 3: Table of Comparison Shape Matching Methods

	References	Shape model	Triangle inequality	Efficiency	Discriminative power	Partial matching	Robustness	Normalization required
Global feature	[21, 28, 42] [67, 88, 89]	all models	yes	fast	low	no	high	no
Global feature distribution	[37, 38, 63] [64, 65, 66]	all models	yes	fast	medium	no	high	only [64]
Spatial map	[5, 30, 43] [46, 47, 61] [84, 85, 86]	all models	yes	fast	high [43, 61, 85]	no	high	not for [30, 43, 61]
Local feature	[18, 41, 45] [74, 87]	mesh	unknown	medium	medium	yes	medium	no
Model graph	[19, 26, 27, 29] [53, 54, 55, 91]	solid except [91]	not applicable in practice	medium	medium	yes	medium	no
Skeleton	[39, 51, 76]	volume	not applicable in practice	medium	medium	yes	medium	no
Reeb graph	[12, 13, 15, 34]	volume	not applicable in practice	medium	medium	yes	medium	no
View	[17, 22, 30] [49, 52]	mesh	[17]	medium	high [17]	no	high	no
Volumetric error	[60, 69]	volume	[69]	fast [60]	medium	no	high	yes
Weighted point set	[24, 72, 78]	mesh	[78]	medium	medium	no	medium	yes
Deformation	[23, 79]	mesh	unknown	slow	medium	no	high	no

We stored the hose shapes as an array of x-y coordinates. As discussed previously, this is not ideal for a fully functioning database. However, for the purposes of our research, flexible shapes are easier to represent and manually manipulate as an array of Cartesian coordinates. But if the SRPCS became a fully functioning tool, we suggest that the flexible component database be represented as a collection of shape histograms.

A.3 Core Properties

The geometric data can be defined as any property that would determine the form of the flexible component. Both the length and the cross section of the hose are required to completely define the hose geometry. Three parameters are required for this: length (L), outer diameter (D_o), and inner diameter (D_i). It would be possible to represent the cross section of the hose with different parameters, such as mean diameter and wall thickness. However, hose specifications are often given in outer and inner measurements, thus seem most appropriate. Once the three parameters are known, several other properties can be computed such as area moment of inertia.

$$I = \frac{\pi}{64} (D_o^4 - D_i^4)$$

The geometric properties of a hose are completely defined by the three aforementioned parameters. We also need to define the material properties of the flexible component. The most important material property that needs to be stored relates to the ‘stiffness’ of the component. Researchers use various methods for this. However, nearly all sources are united in their determination of the elastic modulus (sometimes called the Young’s modulus) as a core property. To determine elastic modulus, each type of flexible component must be individually tested. The elastic modulus was found in [12] by, “mounting a length of hose as a cantilever and measuring its deflection.” The modulus can then be found using:

$$E = \frac{wL^4}{8yI}$$

where w is the weight per unit length of the hose and y is the end deflection. However, because the hoses we use have a rest curvature, this method can prove inaccurate. As an alternative, the traditional approach can be used, where the hose is placed in a load cell. The elastic modulus is the slope the stress-strain curve in the elastically deformable region.

One of the most important properties associated with hose shape are the boundary conditions (BC). BC’s include many different parameters. The hose endpoints are set a certain distance from each other as shown in Figure 30. These distances are the longitudinal and lateral spacing. The BC’s also form an attachment angle with each other. In our testing this attachment angle was always 0 degrees, 90 degrees or 180 degrees. The boundary conditions themselves could be several different types (fixed, hinged, free rotating). However, nearly all automobile

hose attachments use a fixed attachment method. So for the purposes of this research, all hose attachments were assumed to be fixed.

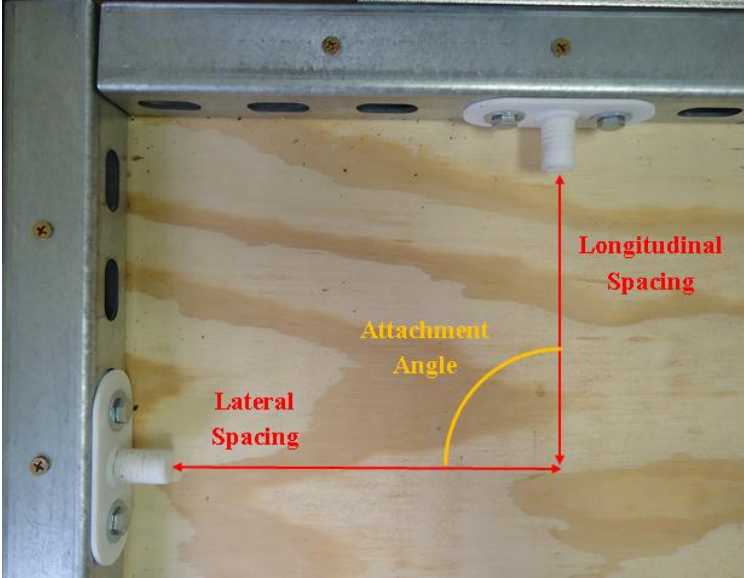


Figure 30: Boundary Condition Properties

Table 4 shows a revised list of core properties to store with the hose shape. This list is what is currently believed to be large enough to generate reliable shape predictions and small enough to search a database in a simple, fast manner. As more experience is gained in this field, there may be modifications on what is deemed important as a ‘core’ property.

Table 4: Core Properties

Core Properties	Variable
Length	L
Area Moment of Inertia	I
Young’s Modulus	E
Longitudinal Spacing	y
Lateral Spacing	x
Attachment Angle	θ

A.4 File Organization

This section explains how our flexible component data is stored and organized. All of the flexible component shapes are stored in the file folder ‘Hose Shapes.’ The most often referenced shapes are the atomic shapes. These are all found in the sub-folder ‘Atomic Shapes.’ The files are labeled under the following format: “Hose Type”_”Hose Length”_”Bend Condition.” The hose type is classified as A or B, which are the two types of water hoses. The hose length refers to whether the hose is 400, 600, or 1200 mm long. And the bend condition identifies if the attachment angle is 0, 90, or 180 degrees. Within each individual file is where the shapes are stored.

When the array of points is gathered for a specific test scenario, the points are first entered into the spreadsheet under the i and j columns. The spreadsheet then automatically shifts the array into x and y columns, which starts the shape at x=0, y=0. The core properties are stored in this spreadsheet. We display a chart of the array of points as well. These charts are sized such that the shape is not skewed in the x or y direction. The units for the numbers on the axis are in millimeters. Every atomic shape follows this storage format and is assigned a number. The number does not provide an indication of the shape, but is only used for distinguishing purposes. The file “Non-Atomic Shapes” is set up in the same way as the spreadsheets used to store the atomic shapes.

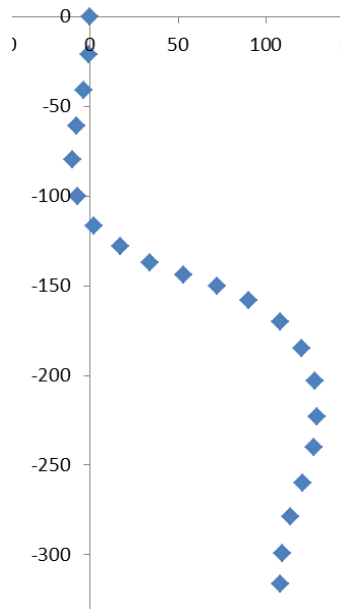


Figure 31: Atomic Shape 17

Also in that sub-folder is a file called “Atomic Shapes All.” The file consists of a spreadsheet with all of the shapes in one location. This is essentially our database. Also in this file is a table where all of the similarity measures are calculated.

The sub-folder “Tests” contains the information used in Chapter 4. The file “Atomic Averages” corresponds to Section 4.6 and file “ShrinkExpand” corresponds to Section 4.6.2. Also, the file named “Tests - Nonatomic” shows the steps used for shape matching using the SRPCS approach laid out in Chapter 5.

A.5 Differing Shapes

The question was raised which hose shape to use when determining how to interpolate a solution. This was tested in several cases displayed in the ‘Tests - Atomic Averages’ document.

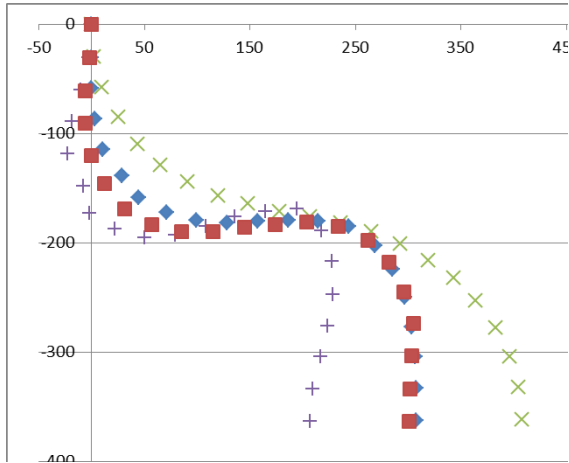


Figure 32: Test Case 21

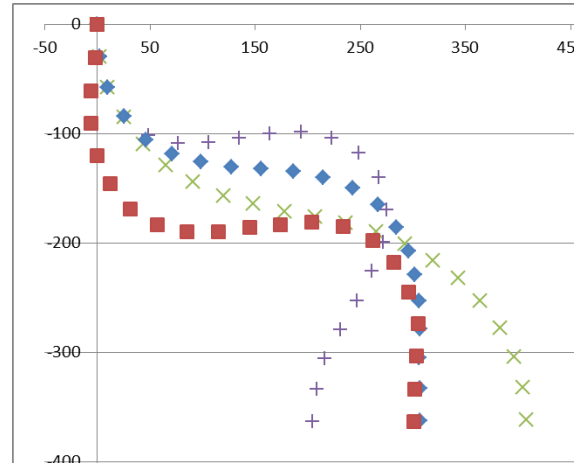


Figure 33: Test Case 22

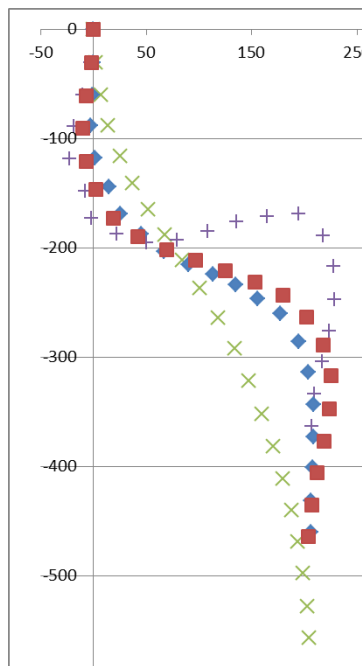


Figure 34: Test Case 25

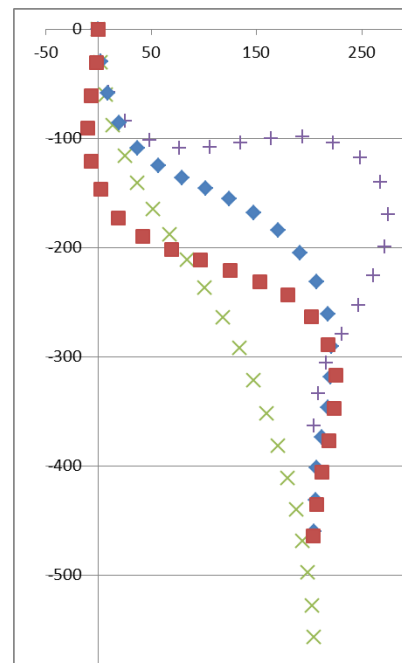


Figure 35: Test Case 26

In these examples the green and purple arrays (which represent actual shapes) were averaged with each other to produce the blue. This was compared with the red, which is an actual hose shape representing the ‘middle case’ between the green and purple. The purple array was

changed between the asymmetric configurations and symmetric configurations that the hose took in testing (Figure 32 and Figure 34 represent the symmetric configuration; Figure 33 and Figure 35 represent the asymmetric configuration).

One can see that a better match was interpolated when the symmetric configuration was used rather than the asymmetric configuration. So it would appear that it always makes sense to use the symmetric bent case. However, in one test case (Figure 36), using the asymmetric test case to predict hose shapes makes more sense than the symmetric case. In this trial, the hose with two configurations was the ‘middle case.’ The asymmetric shape (light blue circles) was closer to the average (blue diamonds) than the symmetric shape (red squares).

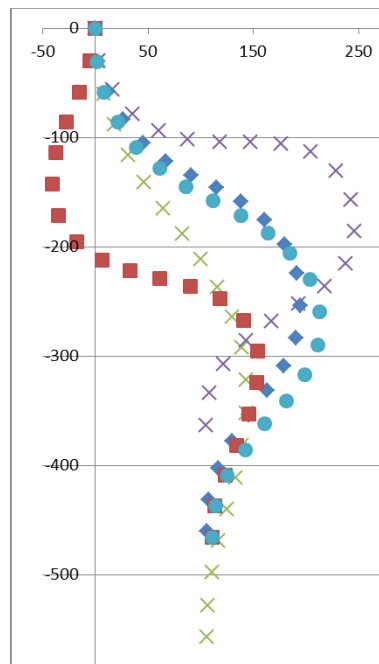


Figure 36: Test Case 24

A.6 The Deviation Ratio

Figure 37, Figure 38, and Figure 39 break down show the LSR-DR relationship as individual 90, 0, and 180 degree bend cases.

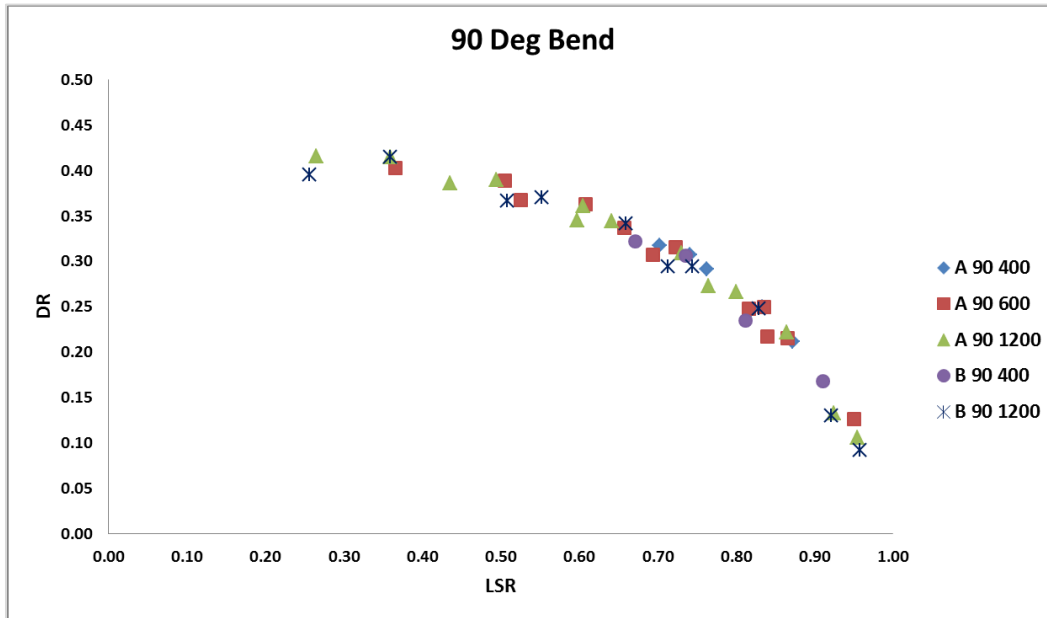


Figure 37: DR vs LSR for 90 Degree Bend Case

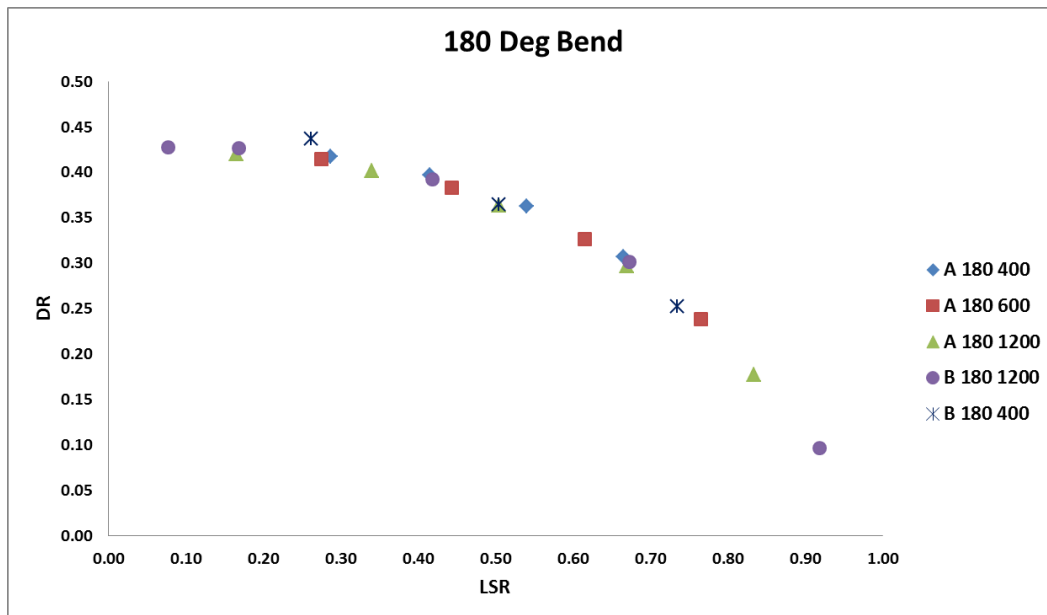


Figure 38: DR vs LSR for 180 Degree Bend Case

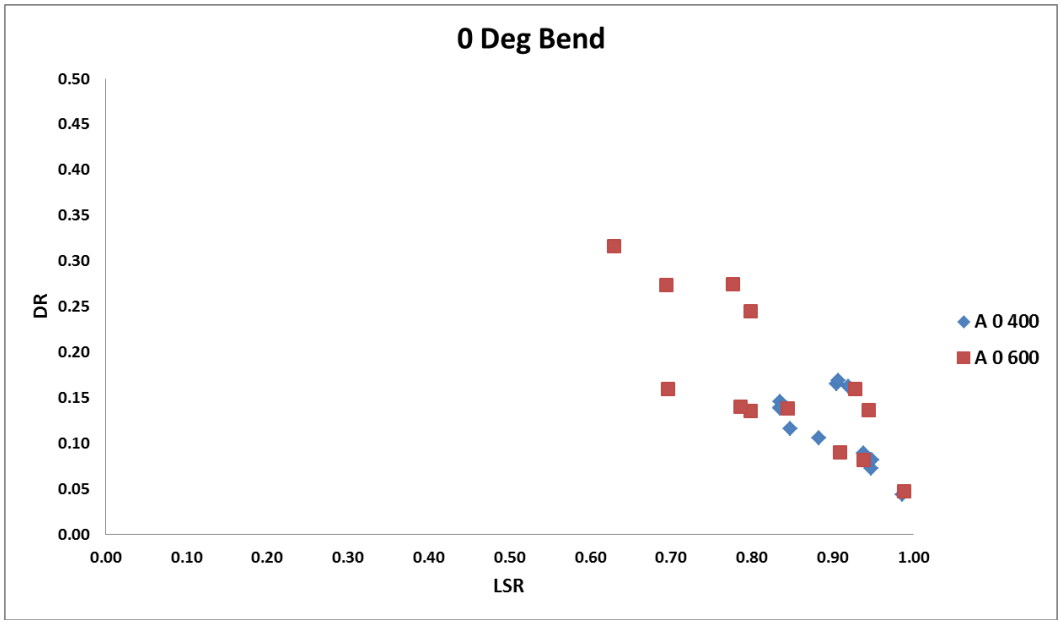


Figure 39: DR vs LSR for 0 Degree Bend Case

A.7 Non-Atomic Shape Matching

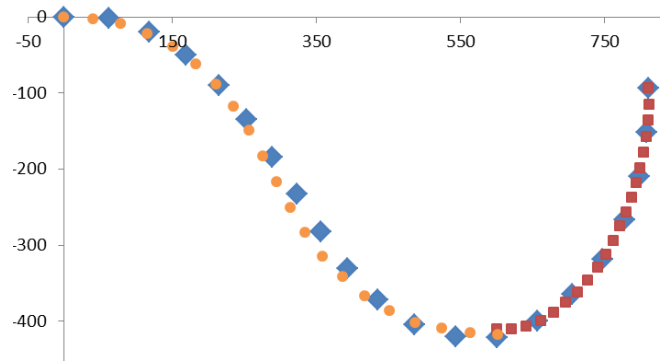


Figure 40: Test S2

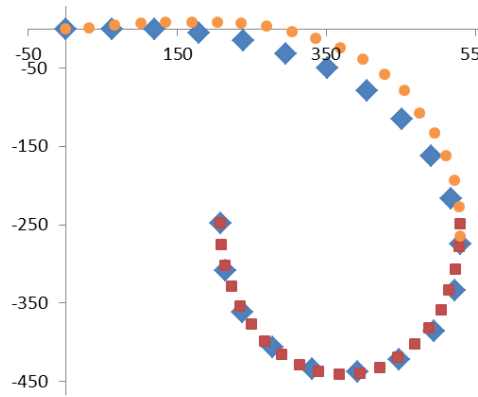


Figure 41: Test S3

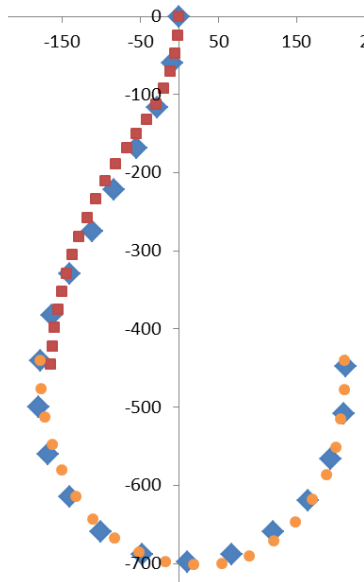


Figure 42: Test S4

A.8 Design Project

Hoses are used to transport fluids for a variety of applications in the automotive industry. Examples include brake hoses, fuel lines, formed radiator hoses, CV joint boots, and stabilizer bars. Multiple electrical wires can be combined together as flexible cables, which behave in a similar manner to hoses. One of the most important aspects of flexible hoses and cables is the shape they will take under different conditions, also called routing. Routing can be defined as the path a flexible component takes between two endpoints. Unlike other rigid components, flexible components must have the ability to offer consistent performance while withstanding large deformations. These hoses and cables must also deflect in ways that result in favorable geometric conditions. Thus, accurately predicting the routing of flexible components is essential to the continued improvement of automobile design.

Current research is underway which attempts to predict the shapes of flexible components in a new way. Most of the current approaches for predicting flexible component shapes involve mathematical solutions methods through Computer Aided Engineering (CAE) software, such as Finite Element models. We propose a new approach where the solution is ‘looked-up,’ rather than calculated. The new approach is known as the Search-based Real-time Predictor of CAE Solutions (SRPCS).

The SRPCS approach requires a large database of intelligently represented solutions to known problems. However, existing databases of hose and cable shapes do not exist. Researchers who wish to work with a database of flexible component shapes must generate the data themselves. In their research, Herrmann and Patil, constructed a test rig and generated a database of hose shapes to prove the validity of the SRPCS process. However, the simplified construction of the test rig had several limitations including:

- All of the hoses were stored as 2 dimensional shapes.
- The endpoint conditions were varied in 2 dimensions.
- The endpoints of the hoses were always oriented at 90 degree intervals from each other.
- The hoses were never pressurized.

To further develop this research, a new experimental setup must be constructed which does not have the limitations of the previous test rig.

This new test rig must meet the following requirements:

- Accurately measure and record the shape of a hose or cable in 3 dimensions

- Modify the endpoint conditions in 3 dimensions so multiple scenarios can be simulated.
- Pass pressurized fluid through a hose similar to values encountered in the automotive industry.
- Vary the pressure of fluid passing through a hose.

This project would require a student or group of students to carry out the following tasks:

- Research and understand the work that has been completed in this field.
- Meet with the advisor of this research project on a regular basis.
- Design a new test rig in CAD software such as Pro/Engineer or SolidWorks.
- Construct test rig.
- Develop experimental procedure for setting up hoses, recording the shape, and storing it in a database.