Half car vehicle system assignment

Introduction (Vehicle suspension analysis using Fuzzy Logic) Generally for analysis of vehicle suspension systems various types of vehicle suspension models were taken by the researchers. The most commonly used models are 1. Quarter car model 2. Half car model 3. Full car model The details of the three types are discussed below 1. 1 Quarter car model On this particular model, only ? of the vehicle is taken into consideration to develop a vehicle suspension low level controller. Model is a two dimensional model because only movement on z direction is taken into consideration.

The general representation of a quarter car model is shown in figure 1. 1. It basically consists of a single wheel which is represented in the form of a spring. However in some cases the wheel can be considered as equivalent to a parallel combination of spring and a damper. The actual shock absorber is assumed to support only one fourth of the weight of the total car body mass including passenger’s weight. Fig 1. 1 Quarter car model The advantages of these types of models are that they are simple and easy to analyze mathematical relations involved in the model. 1. Half car model Unlike quarter car model where only one wheel is analyzed half car model considers two wheels, viz. one front and one rear wheel. In this type of models half of the weights of the entire car including that of passengers are considered for analysis purpose. The main advantages of this type of models are 1. Vehicle pitch motions can be simulated. 2. Front and rear dampers and spring characteristics can be modeled differently which is also different on the actual vehicle. 3. Body motions and center of gravity effect can be simulated. Fig 1. 2 Half car model Fig 1. 2 shows the general representation of half car model.

As shown in the figure both the front wheel and back wheel supports half of the car weight by means of separate dampers attached to them. Model is again a two dimensional model which has a movement only on Z direction. Vehicle Models 1. 3 Full Car model In full car model, total weights of the car body as well as the passengers are considered and four wheels were taken for analysis. The pitch and roll motions of the car were also taken into consideration. Model is a three dimensional model which has a movement on Z direction. On full-car model 1. Vehicle pitch and roll motions can be simulated. 2.

Different front and rear suspension system geometries can be modeled (for example, vehicle has independent suspension on the front and a solid dead beam on the rear and this can be geometrically modeled on a full car model). 3. Left and right hand side body and tire motions of the vehicle can be simulated separately. 4. Un-sprung and sprung mass motions can be evaluated for both front & rear right and the left hand side suspension systems. A full-car model is based on the four identical quarter-car models, which are coupled together by solid rods with respect to pitch and roll moment of inertia.

Then braking, accelerating and steering influences should be reflected, i. e. longitudinal and lateral acceleration are considered. Therefore vehicle body roll and pitch, which cause the center of gravity movements and this is an important attribute for car stability during driving through the curves. In general, based on the damper used vehicle suspension systems can be classified into three types. They are 1. Passive 2. Semi Active 3. Active suspension systems. Each type has its own advantages and disadvantages.

However semiactive and active models are the one most commonly used in practical applications.

The details of the three types are given in the following sections. 1. 4 Passive suspension system Passive suspension system consists of an energy dissipating element, which is the damper, and an energy-storing element, which is the spring. Since these two elements cannot add energy to the system this kind of suspension systems are called passive. Figure 1. 4 shows Passive suspension system considered in this study. Fig 1. 4 Passive suspension system 1. 5 Semi Active Suspension System To replace complexity and cost while improving ride and handling the concept of semi active suspension has emerged.

In this kind of suspension system, the passive suspension spring is retained, while the damping force in the damper can be modulated (adjusted) in accordance with operating conditions. Figure 1. 3 shows the schematic view of a semi active suspension system. The regulating of the damping force can be achieved by adjusting the orifice area in the damper, thus changing the resistance of fluid flow. Most recently the possible application of electro-rheological and magneto-rehological fluids to the development of controllable dampers has also attracted considerable interest.

Fig 1. 5 Semiactive suspension system 1. 6 Active Suspension System Figure 1. 6 shows an active suspension system in which a force actuator is placed in parallel to passive system. In active suspension systems, sensors are used to measure the accelerations of sprung mass and unsprung mass and the analog signals from the sensors are sent to a controller. The controller is designed to take necessary actions to improve the performance abilities already set. The controller amplifies the signals which are fed to the actuator to generate the required forces o form closed loop system (active suspension system). The performance of this system is then compared with that of the open loop system (passive suspension system) [22]. It should be noted, that an active suspension system requires external power to function, and that there is also a considerable penalty in complexity, reliability, cost and weight [8]. Fig 1. 6 Active suspension system 2. 1 Literature Review The majority of the studies in the area of semiactive suspensions used a twodegree-of freedom (2DOF) model representing single suspensions.

There were a few studies in the area of single-degree-of-freedom (SODF) systems. Lieh explores the use of semiactive suspensions to control the dynamics of a full car model. Fuzzy logic was first presented to the consideration of the academic society by Zadeh (1965) and became popular rapidly. Rao & Prahlad (1997) suggested fuzzy logic based control for vehicle active suspension. Fuzzy logic control methods had been used extensively in recent years in a number of applications. The design of a fuzzy logic control law does not require a mathematical description of the control system.

Whereby in current control scheme, the accurate system model must be provided before the controller can be developed. In addition, an appropriate fuzzy logic controller can take care of the environmental variation during the operation process. Thus, the model-free fuzzy logic control strategy has attracted the attention of the researcher. Two studies, one by Yi and Hedrick and the other by Valesek, were found to be in the area of dynamic tire loading. Both studies were interested in methods to reduce the dynamic tire loading of a vehicle in order to reduce the amount of road damage that it causes.

Three other studies focused on control methods that are able to teach themselves how to control the semiactive suspension system. Cheok and Huang and Yoshimura used fuzzy logic and neural network methods to teach the controller, while Frost uses a moderated reinforcement learning technique. All three studies show that there are benefits associated with these types of control approaches. The next study by Margolis examines the effects of using realistic feedback signals when controlling active and semiactive suspension systems.

This is an analytical study that suggests several feedback strategies for the semiactive suspension system so that the performance can approach the fully active suspension performance. In another study by Margolis, he outlines a procedure to examine the feasibility of using semiactive or active vibration isolation instead of purely passive approaches. Hwang et al. present an interesting method for testing the semiactive damper hardware without using a complete vehicle. They explore the test method known as hardware in the loop simulation. Essentially, the dynamic model of the system is coded for simulation in a computer.

Jezequel and Roberti investigated optimal preview of the suspension system which is useful for trains: once the lead train passes over a point, the rest of the train has knowledge of the track conditions. Miller explored the effects of the levels of both on-state and off-state damping on the performance of the quarter car semiactive suspension system. Bellizzi and Bouc and Hrovat, et al. studied optimal control techniques for the semiactive suspension, while Tibaldi and Zattoni studied the robustness of linear quadratic Gaussian control techniques. Ahmadian et al. In press) designed an active suspension system and implemented to smooth the amplitude and acceleration received by the passenger within the human health threshold limits. A quarter car model is considered and three control approaches namely optimal control, Fuzzy Control, and Adaptive Optimal Fuzzy Control (AOFC) are applied. Bourmistrova et al. (2005) applied evolutionary algorithms to the optimization of the control system parameters of quarter car model. The multi objective fitness function which is a weighted sum of car body rate-of-change of acceleration and suspension travel is minimized.

Sharkawy (2005) described fuzzy and adaptive fuzzy control (AFC) schemes for the automobile active suspension system (ASS). The design objective was to provide smooth vertical motion so as to achieve the road holding and riding comfort over a wide range of road profiles. Roumy et. al. (2004) developed LQR and H? controller for quarter car model. The structure’s modal parameters are extracted from frequency response data, and are used to obtain a state-space realization. The performance of controller design techniques such as LQR and H? is assessed through simulation.

Because of active suspension systems’ expenses, in this paper, semiactive suspension systems are investigated. Several control methods have been used by Nicolas et al. and Son et al. in semi-active suspension systems. Active vehicle suspensions have attracted a large number of researchers in the past few decades and comprehensive surveys on related research are found in publications by Elbeheiry (1995), Hedrick and Wormely (1975), Sharp and Crolla (1987), Karnopp (1995) and Hrovat(1997). Again, Yoshimura et al (1999) presented an active suspension system for passenger cars, using linear and fuzzy-logic controls in their study.

Ahmadian et al. (In press) designed an active suspension system and implemented to smooth the amplitude and acceleration received by the passenger within the human health threshold limits. A quarter car model is considered and three control approaches namely optimal control, Fuzzy Control, and Adaptive Optimal Fuzzy Control (AOFC) are applied. Sakman et al (2005) examined the performance of the fuzzy logic controlled active suspensions on a non-linear vehicle model having four degrees of freedom without causing any loss in suspension working limits.

Lazareva and Shitik studied the properties of MR fluids that are based on barium and strontium ferrites and iron oxides. The fluids were prepared using various combinations of the materials, and their properties, such as the MR effect, were studied. Ashour et al. studied the effects of components of the MR on sedimentation of the magnetic particles and initial viscosity. An attempt was made to optimize the composition of the fluid such that the fluid had the desired properties. In another study, Ashour et al. studied the general composition of MR fluid along with the methods that are used to evaluate the performance of the fluids. . 2 Objectives of the present work The present work aims at developing a Fuzzy logic controller for one of the types of half car suspension system (viz. semiactive suspension system) and focus on comparing the obtained results with that of general passive suspension system inorder to reduce the sprung mass displacement for ride comfort, by considering two different road profiles. Semiactive suspension system is especially considered in this work because of the fact that these systems are cost effective, compact, and functionally simple as they require only a variable damper and a few sensors to achieve adequate performance.

Active suspensions systems remain complex, bulky, and expensive and are not common options on production vehicles. Additionally, they typically require considerable power and impose heavy loads on the engine. – Half Car Model Mathematical formulation In order to simulate the suspension system mathematical equations, which represent the suspension system is to be first derived. For this reason fundamental principle of mechanics was applied. In order to formulate mathematical relations for sprung and unsrung masses, some simple assumptions were considered in this work. . 1 Assumptions 1. Vehicle wheels does not leave the ground 2. Mass (m, sprung mass) is assumed to be distributed uniformly over the undercarriage and the entire mass is assumed to act at the CG 3. Pitch angle is considered very small 4. Velocity of the vehicle is constant 3. 2 Passive model description Based on these assumptions the half car system was split into two separate quarter car systems, the combined behavior of the two being the same as the half car itself. The tire is simply modeled as a spring of stiffness Ku. Figure 3. shows the half car model represented with suitable notations. Fig 3. 1 half car representation of passive suspension system Fig 3. 2 Quarter car representation of front wheel Fig 3. 3 Quarter car representation of Rear wheel Let m be the one half the mass of total vehicle xb be the vehicle (body) displacement m1, m2 be the unsprung masses of front and rear wheels ms1, ms2 be the sprung masses of front and rear wheels Kb1 , Kb2 be the spring constants of front and rear springs Kw1 , Kw2 be the spring constants of front and rear wheels b1 , cb2 be the damper coefficients for dampers of front and rear wheels x5 , x6 be the displacements of front and rear sprung masses x2 , x4 be the displacements of front and rear unsprung masses x1 , x3 be the displacements of front and rear wheels (road profiles) Ib Pitch inertia L1 L2 be the distance of CG from front and back suspensions Using the above notations the mathematical relations is derived as fallows 3. 2. 1 Equivalent masses The equivalent masses ms1, ms2 is given by ms1 = m L2 / (L1 + L2) ms2 = m L1 / (L1 + L2) 3. 2. 2 Equations of motion (3.) (3. 2) m1 x2 ” = Kw1 (x1 ? x2) ? Kb1 (x2 ? x5) ? cb1 (x2′ ? x5′) (3. 3) m2 x4″ = Kw2 (x3 – x4) ? Kb2 (x4 – x6) ? cb1 (x4′ – x6′) ms1 x5 ” = Kb1 (x2 ? x5) + cb1 (x2′ ? x5′) = F1 ms2 x6 ” = Kb2 (x4 – x6) + cb1 (x4′ – x6′) = F2 where (3. 4) (3. 5) (3. 6) x5 = xb + L 1 ? x6 = xb ? L 1 ? The pitch angle, ? is obtained by the torque relation as F 1 L1 – F 2 L2 = I b ? 3. 2. 3 Pitch angle equation ” (3. 7) (3. 8) (3. 9) Pitch angle can be obtained by substituting equations 3. 5 and 3. 6 in 3. 9 and then double integrating the acceleration ? Thus ” ?” = L1 / Ib [Kb1 (x2 ? x5) + cb1 (x2′ ? x5′)] – L2 / Ib [Kb2 (x4 – x6) + cb1 (x4′ – x6′)] 3. 2. 4Equation for body displacement The body displacement (3. 10) xb is obtained by as fallows; substituting ? from ” equation 3. 9 in equation 3. 7 by differentiating twice the equation 3. 7, we get xb” = x5 ” ? L1 / Ib (F1 L1 – F2 L2) Substituting F1, F2 from the equations 3. 5, 3. 6 in 3. 11 (3. 11) xb” = x5 ” ? L1? / Ib [Kb1 (x2 ? x5) + cb1 (x2′ ? x5′)] + L2 L1 / Ib [Kb2 (x4 – x6) + cb1 (x4′ – x6′)] Solving 3. 5 and 3. 2, we get (3. 12) xb” = Kb1/ ms1 (x2 ? x5) + cb1 / ms1 (x2′ ? x5′) – L1? / Ib [Kb1 (x2 ? x5) + cb1 (x2′ ? x5′)] + L2 L1 / Ib [Kb2 (x4 – x6) + cb1 (x4′ – x6′)] (3. 13) ? xb” = Kb1 [1/ ms1 ? L1? / Ib] (x2 ? x5) + cb1 [1/ ms1 ? L1 / Ib] (x2′ ? x5′) + (3. 14) L2 L1 / Ib [Kb2 (x4 – x6) + cb1 (x4′ – x6′

)] xb” = [1/ ms1 ? L1? / Ib] [Kb1 (x2 ? x5) + cb1 (x2′ ? x5′)] + L2 L1 / Ib [Kb2 (x4 – x6) + cb1 (x4′ – x6′)] Equation 3. 15 can be used to find the body displacement of the vehicle. (3. 15) 3. 3 Semiactive model description

The equations of motions for semiactive suspension system are similar to that of passive system, except that the constant damping coefficients cb1, cb2 were replaced by variable damping coefficients for both front and rear wheels. Figure 3. 4 shows the quarter car representations of the half car model. (a) (b) Fig 3. 4 Quarter car representation for (a) front (b) rear wheel 4. 1 Passive dampers Shocks absorbers are used to damp oscillations by absorbing the energy contained in the springs or torsion bars when the wheels of an automobile move up and down. Conventional shock absorbers do not support vehicle weight.

They reduce the dynamic wheel-load variations and prevent the wheels from lifting off the road surface except on extremely rough surfaces and making possible much more precise steering and braking. The shock absorbers turn the kinetic energy of suspension motion into thermal energy, or heat energy, to be dissipated through the hydraulic fluid [4]. In passive suspension vehicles two types of hydraulic shock absorbers are generally used. They are 1. Mono tube shock absorbers 2. Twin tube shock absorber The compression cycle controls the motion of a vehicle’s unsprung weight, while extension controls the heavier sprung weight. . 1. 1 Mono tube shock absorber 1. Compression stroke: During the compression stroke or downward movement, some fluid flows through the piston from chamber B to chamber A and some through the compression valve into the reserve tube. To control the flow, there are three valving stages each in the piston and in the compression valve. Figure 4. 1 shows the monotube absorber during compression cycle. At the piston, oil flows through the oil ports, and at slow piston speeds, the first stage bleeds come into play and restrict the amount of oil flow. This allows a controlled flow of fluid from chamber B to chamber A.

At faster piston speeds, the increase in fluid pressure below the piston in chamber B causes the discs to open up away from the valve seat. At high speeds, the limit of the second stage discs phases into the third stage orifice restrictions. Compression control, then, is the force that results from a higher pressure present in chamber B, which acts on the bottom of the piston and the piston rod area. Fig 4. 1 mono tube absorber during compression cycle 2. Extension stroke: As the piston and rod move upward toward the top of the pressure tube, the volume of chamber A is reduced and thus is at a higher pressure than chamber B.

Because of this higher pressure, fluid flows down through the piston’s 3-stage extension valve into chamber B. However, the piston rod volume has been withdrawn from chamber B greatly increasing its volume. Thus the volume of fluid from chamber A is insufficient to fill chamber B. The pressure in the reserve tube is now greater than that in chamber B, forcing the compression intake valve to unseat. Fluid then flows from the reserve tube into chamber B, keeping the pressure tube full. Extension control is a force present as a result of the higher pressure in chamber A, acting on the topside of the piston area.

Figure 4. 2 shows the mono tube absorber during extension or rebound cycle. . Fig 4. 2 mono tube absorber during extension cycle 4. 1. 2 Twin tube

Shock absorbers The main components of a Twin tube shock absorber are: • • • outer tube, also called reservoir tube inner tube, also called cylinder piston connected to a piston rod • • bottom valve, also called footvalve piston rod guide Twin-Tube Shock Absorber Working Compression stroke: When the piston rod is pushed in, oil flows without resistance from below the piston through the outlets and the non-return valve arranged to the area above the piston.

Simultaneously, a quantity of oil is displaced by the volume of the rod entering the cylinder. This volume of oil is forced to flow through the bottom valve into the reservoir tube filled with air or nitrogen gas. The resistance, encountered by the oil on passing through the footvalve, generates the bump damping. Fig 4. 3 Twin tube shock absorber Rebound stroke: When the piston rod is pulled out, the oil above the piston is pressurized and forced to flow through the piston. The resistance, encountered by the oil on passing through the piston, generates the rebound damping.

Simultaneously, some oil flows back, without resistance, from the reservoir tube through the foot valve to the lower part of the cylinder to compensate for the volume of the piston rod emerging from the cylinder. A number of types of twin tube hydraulic shock absorbers with minor refinements are available. Basic refinements offered can be classified into: 1. 2. Adjustable damping co-efficient Variable damping co-efficient type. In case of Mono-tube, the shell case itself works as a cylinder and oil, gas, piston valve, etc are all set in a single tube. Fig 4. Mono-Twin Tube Shock Absorbers Each type has its own advantages and disadvantages, the details of which are given below 4. 2 Comparison of Two Shock Absorbers 4. 2. 1 Twin-Tube Shock

Absorber The advantages and disadvantages of the twin-tube shock absorber [4] are: Advantages: 1. Allows ride engineers to move beyond simple velocity sensitive on the valves and to use the position of the piston to fine tune the ride characteristic. 2. Adjusts more rapidly to changing road and weight conditions than single-tube shock absorbers. 3. A control is enhanced without sacrificing driver comfort.

Two shocks absorbers into one comfort and control. Disadvantages: 1. Can only be mounted in one direction. Current Uses: 1. Original equipment on many domestic passenger cars, SUV and light truck applications. 4. 2. 2 Single-Tube Shock Absorber The advantages and disadvantages of the single-tube designs are: Advantages: 1. Easy to tailor to specific applications, as the larger piston diameter allows low working pressures. 2. 3. Sufficient room for valves and passages. Can be installed in any position, can be mounted upside down, reducing the unsprung weight. 4. the air.

Disadvantages: 1. 2. May run cooler. Heat is dissipated directly via the outer tube because it is exposed to Longer than twin-tube shock absorbers. The outer tube, which acts as a guide cylinder for the piston, is susceptible to damage from stone throw, etc. A dent in the pressure tube will destroy the unit. 3. Suspension layout must provide sufficient room for the tube which, with its very close tolerances, is not to be mechanically impeded in any way. This is a disadvantage when lines must be routed around the shock absorber in restricted bodywork areas. 4. 5.

The piston rod seal is subjected to the damping pressure. Difficult to apply to passenger cars designed OE with twin-tube designs. Current Uses: 1. Original equipment for many import and domestic passenger cars, SUV and light truck applications. 2. Available for many after market applications. 4. 3 Magneto Rheological Dampers Magneto-rheological (MR) fluids are suspensions of micron-sized, magnetizable particles in an oil based fluid. In the absence of magnetic fields, these fluids exhibit Newtonian behavior [2]. Magnetorheological fluids are materials that exhibit a hange in rheological properties (elasticity, plasticity, or viscosity) with the application of a magnetic field. The MR effects are often greatest when the applied magnetic field is normal to the flow of the MR fluid [7]. 4. 3. 1 MR fuids Magneto-rheological fluids consist of ferromagnetic particles that are suspended in a carrier fluid. MR fluid consists of a liquid carrier, ferrous particles on the order of a few microns in diameter, and surfactant additives that are used to discourage particle settling. The ferromagnetic particles are often carbonyl particles, since they are relatively inexpensive.

Other particles, such as iron-cobalt or iron-nickel alloys, have been used to achieve higher yield stresses from the fluid [6]. Fluids containing these alloys are impractical for most applications due to the high cost of the cobalt or nickel alloys. Although similar in operation to electro-rheological (ER) fluids and ferrofluids, MR devices are capable of much higher yield strengths when activated. A wide range of carrier fluids such as silicone oil, kerosene, and synthetic oil can be used for MR fluids. The carrier fluid must be chosen carefully to accommodate the high temperatures to which the fluid can be subjected.

The carrier fluid must be compatible with the specific application without suffering irreversible and unwanted property changes. The MR fluid must also contain additives to prevent the sedimentation of, and promote the dispersion of, the ferromagnetic particles. Besides the rheological changes that MR fluids experience while under the influence of a magnetic field, there are often other effects such as thermal, electrical, and acoustic property changes. In the area of vibration control, however, the MR effect is most interesting because it is possible to apply the effect to a hydraulic damper.

The MR fluid essentially allows one to control the damping force of the damper by replacing mechanical valves commonly used in adjustable dampers. This offers the potential for a superior damper with little concern about reliability since if the MR damper ceases to be controllable; it simply reverts to a passive damper [6]. The major difference between ferrofluids and MR fluids is the size of the polarizable particles [7]. Three different carrier fluids are currently used, namely hydrocarbon-based oil, silicon oil, and water [2].

When exposed to a magnetic field, the ferrous particles within the fluid line up in columnar structures along lines of magnetic flux. These columnar structures cause a distinct change in the apparent viscosity of the MR fluid. The reason why the phrase " apparent viscosity" is used instead of " viscosity" is that the carrier fluid exhibits no change in viscosity, but the MR fluid mixture thickens—even becoming a solid —when it is exposed to a magnetic field. The magnetic field changes the shear strain rate of the MR fluid, in the same sense that the fluid becomes more sensitive to shearing with an increasing magnetic field.

MR fluids are non-colloidal suspensions of magnetizable particles that are on the order of tens of microns (20-50 microns) in diameter. MR fluid is composed of oil, usually mineral or silicone based, and varying percentages of ferrous particles that have been coated with an anti-coagulant material. When inactivated, MR fluid displays Newtonian-like behavior [2]. When exposed to a magnetic field, the ferrous particles that are dispersed throughout the fluid form magnetic dipoles. These magnetic dipoles align themselves along lines of magnetic flux, as shown in figure 4. 5. Fig 4. Dipole alignment of ferrous particles Typically, MR fluid can be used in three different ways, all of which can be applied to MR damper design depending on the damper's intended use. These modes of operation are referred to as squeeze mode, valve mode, and shear mode. A device that uses squeeze mode has a thin film (on the order of 0. 020 inch) of MR fluid that is sandwiched between paramagnetic pole surfaces as shown in figure 4. 6. Fig 4. 6 Squeeze mode As depicted in Figure 4. 7, MR fluid device is said to operate in shear mode when a thin layer (? 0. 005 to 0. 015 inch) of MR fluid s sandwiched between two paramagnetic moving surfaces. The shear mode is useful primarily for dampers that are not required to produce large forces or for compact clutches and brakes. Fig 4. 7 MR fluid used in shear mode The last mode of MR damper operation, valve mode, is the most widely used of the three modes. An MR device is said to operate in valve mode when the MR fluid is used to impede the flow of MR fluid from one reservoir to another, as is shown in figure 4. 8, With the exception of a single hybrid MR damper design, all of the dampers used in this project operate in the valve mode

Fig 4. 8 MR fluid in valve mode 4. 3. 2 Construction of a MR damper A functional representation of an MR damper, with schematics of the components necessary for operation, is shown in figure 4. 9. The fluid that is transferred from above the piston to below (and vice versa) must pass through the MR valve. The MR valve is a fixed-size orifice with the ability to apply a magnetic field, using an electromagnet, to the orifice volume. This magnetic field results in a change in viscosity of the MR fluid, causing a pressure differential for the flow of fluid in the orifice volume.

The pressure differential is directly proportional to the force required to move the damper rod [7]. As such, the damping characteristic of the MR damper is a function of the electrical current flowing into the electromagnet. This relationship allows the damping of an MR damper to be easily controlled in real time. Fig 4. 9 Functional Representation of an MR Damper The accumulator is a pressurized volume of gas that is physically separated from the MR fluid by a floating piston or bladder. The accumulator serves two purposes. The first is to provide a volume for the MR fluid to occupy when the shaft is inserted into the damper cylinder.

The second is to provide a pressure offset so that the pressure in the low pressure side of the MR valve does not induce cavitation in the MR fluid by reducing the pressure below the vapor pressure of the MR fluid. The actual configuration of an MR damper is shown in Fig 4. 10. All of the external components have been incorporated internally, providing a compact design that is very similar in size and shape to existing passive vehicle dampers. The only external parts are the two electrical leads for the electromagnet, which are connected to the current source.

Fig 4. 10 Schematic Representation of MR damper The application of an external magnetic field causes the particles to become aligned with the field, and dramatically changes the effective viscosity of the fluid. Depending on the strength of this applied magnetic field, the viscosity (or yield strength) of MR fluids can reach that of Bingham solids, making them well-suited to semiactive damping applications [3]. Semiactive vehicle suspensions are controlled by manipulating the coil current in the MR damper to vary its effective damping coefficient.

Fig 4. 11 Semiactive controller using MR damper Varying the magnetic field strength has the effect of changing the apparent viscosity of the MR fluid. The reason why the phrase " apparent viscosity" is used instead of " viscosity" is that the carrier fluid exhibits no change in viscosity, but the MR fluid mixture thickens—even becoming a solid—when it is exposed to a magnetic field. The magnetic field changes the shear strain rate of the MR fluid, in the same sense that the fluid becomes more sensitive to shearing with an increasing magnetic field.

As the magnetic field strength increases, the resistance to fluid flow at the activation regions increases until the saturation current has been reached. The saturation current occurs when increasing the electric current fails to yield an increase in damping force for a given velocity. The resistance to fluid flow in the activation regions is what causes the force that MR dampers can produce. This mechanism is similar to that of hydraulic dampers, where the force offered by hydraulic dampers is caused by fluid passage through an orifice.

Variable resistance to fluid flow allows us to use MR fluid in electrically controlled viscous dampers and other devices. Figure 4. 12 shows the general representation of a usual MR damper Fig 4. 12 Typical MR damper 4. 3. 3 Types of MR Dampers There are three main types of MR dampers. These are 1. mono tube 2. twin tube 3. double-ended MR damper Mono tube MR damper Of the three types, the mono tube is the most common since it can be installed in any orientation and is compact in size. A mono tube MR damper, shown in Figure 4. 3, has only one reservoir for the MR fluid and an accumulator mechanism to accommodate the change in volume that results from piston rod movement. The accumulator piston provides a barrier between the MR fluid and a compressed gas (usually nitrogen) that is used to accommodate the volume changes that occur when the piston rod enters the housing [7]. Fig 4. 13 Mono tube MR damper The popularity of mono tube dampers (not only MR types) is due mainly to their compact size, reliability, and their ability to function properly in any installed orientation.

Twin tube MR damper The twin tube MR damper is one that has two fluid reservoirs, one inside of the other, as shown in Figure 4. 14. In this configuration, the damper has an inner and outer housing. The inner housing guides the piston rod assembly, in exactly the same manner as in a mono tube damper. The volume enclosed by the inner housing is referred to as the inner reservoir. Likewise, the volume that is defined by the space between the inner housing and the outer housing is referred to as the outer reservoir. The inner reservoir is filled with MR fluid so that no air pockets exist.

To accommodate changes in volume due to piston rod movement, an outer reservoir that is partially filled with MR fluid is used. Therefore, the outer tube in a twin tube damper serves the same purpose as the pneumatic accumulator mechanism in mono tube dampers. In practice, a valve assembly called a “ foot valve” is attached to the bottom of the inner housing to regulate the flow of fluid between the two reservoirs. As the piston rod enters the damper, MR fluid flows from the inner reservoir into the outer reservoir through the compression valve, which is part of the foot valve assembly.

The amount of fluid that flows from the inner reservoir into the outer reservoir is equal to the volume displaced by the piston rod as it enters the inner housing. As the piston rod is withdrawn from the damper, MR fluid flows from the outer reservoir into the inner reservoir through the return valve, which is also part of the foot valve assembly. Fig 4. 14 Twin tube MR damper Double-ended MR damper The final type of MR damper is called a double-ended damper since a piston rod of equal diameter protrudes from both ends of the damper housing. Figure 4. 15 shows a section view of a typical double-ended MR damper.

Since there is no change in volume as the piston rod moves relative to the damper body, the double-ended damper does not require an accumulator mechanism. Double-ended MR dampers have been used for bicycle applications, gun recoil applications, and for controlling building sway motion caused by wind gusts and earthquakes. Fig 4. 15 Double-ended MR damper 4. 3. 4 Performance of the MR Damper For typical passive dampers, the damper performance is often evaluated based on the force vs. velocity characteristics. For a linear viscous damper, the force vs. velocity performance is shown in Fig. 4. 16.

The slope of the force vs. velocity line is known as the damper coefficient, C. Fig 4. 16 Linear Damper Characteristics In practice, however, the force vs. velocity line is frequently bilinear and asymmetric, with a different value of C for jounce (compression) and rebound (extension), as shown in Fig 4. 17. The reason for having asymmetric damping characteristics stems from the final application of the damper in a vehicle suspension. When working in series with the primary spring of the vehicle suspension, the damper is working against the spring force in compression and is greatly aided by the spring force in rebound.

If the vehicle encounters a pothole or momentary loss of contact with the road, the only mechanism preventing the suspension from rebounding to the physical stops is the rebound damping [7]. Fig 4. 17 Bilinear and Asymmetric Damping Characteristics In the case of MR dampers, the ideal force-velocity characteristics are as shown in figure 4. 18. The result is a force vs. velocity envelope that is spanned by an area rather than a line in the force-velocity plane. In this ideal case, the damper force is independent of the shaft velocity, and is only a function of the current going into the coil.

Effectively, the controller can be programmed to emulate any damper force-velocity characteristic or control policy within the envelope [7]. Fig 4. 18 Ideal MR Damper Performance We can model the ideal MR damper according to FMRDAMPER = ? Where ? is a constant and i is the damper current. 5. 1 Simulink Simulink refers to the repeated execution of a model at successive time steps as simulating the system that the model represents. Simulink is a software package for modeling, simulating, and analyzing dynamic systems [5].

It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Simulink can be used to explore the behavior of a wide range of real-world dynamic systems, including electrical circuits, shock absorbers, braking systems, and many other electrical, mechanical, and thermodynamic systems. Systems can also be multirate, i. e. , have different parts that are sampled or updated at different rates. For modeling, Simulink provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations.

With this interface, one can draw the models just as one would with pencil and paper (or as most textbooks depict them). This is a far cry from previous simulation packages that require formulate differential equations and difference equations in a language or program. Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. One can also customize and create their own blocks. For information on creating own blocks, see the separate Writing S-Functions guide [5]. Models are hierarchical, so building models using both top-down and bottom-up approaches can be done.

You can view the system at a high level, and then double-click blocks to go down through the levels to see increasing levels of model detail. This approach provides insight into how a model is organized and how its parts interact. After defining a model, one can simulate it, using a choice of integration methods, either from the Simulink menus or by entering commands in the MATLAB Command Window. The menus are particularly convenient for interactive work, while the command-line approach is very useful for running a batch of simulations (for example, if doing Monte Carlo simulations or want to sweep a parameter across a range of values).

Using scopes and other display blocks, it is easy to see the simulation results while the simulation is running. In addition, one can change parameters and immediately see what happens, for “ what if” exploration. The simulation results can be put in the MATLAB workspace for postprocessing and visualization. Model analysis tools include linearization and trimming tools, which can be accessed from the MATLAB command line, plus the many tools in MATLAB and its application toolboxes.

And because MATLAB and Simulink are integrated, one can simulate, analyze, and revise your models in either environment at any point. Simulink is also practical. With thousands of engineers around the world using it to model and solve real problems, knowledge of this tool will serve well throughout engineering professional career [5]. Simulink has the ability to simulate discrete (sampled data) systems, including systems whose components operate at different rates (multirate systems) and systems that mix discrete and continuous components (hybrid systems).

Simulink encourages one to try things out. Models can be easily build from scratch, or take an existing model and add to it. Simulations are interactive, so there is possibility to change parameters on the fly and immediately see what happens. MATLAB has instant access to all the analysis tools, so one can take the results and analyze and visualize them. A goal of Simulink is to give a sense of the fun of modeling and simulation, through an environment that encourages posing a question, modeling it, and seeing what happens.

With Simulink, it is easy to move beyond idealized linear models to explore more realistic nonlinear models, factoring in friction, air resistance, gear slippage, hard stops, and the other things that describe real-world phenomena [5]. Simulink turns the computer into a lab for modeling and analyzing systems that simply wouldn't be possible or practical otherwise, whether the behavior of an automotive clutch system, the flutter of an airplane wing, the dynamics of a predator-prey model, or the effect of the monetary supply on the economy.

A Simulink block diagram model is a graphical representation of a mathematical model of a dynamic system. A mathematical model of a dynamic system is described by a set of equations. The mathematical equations described by a block diagram model are known as algebraic, differential, and/or difference equations. The term `timebased block diagram' is used to distinguish block diagrams that describe dynamic systems from that of other forms of block diagrams. In Simulink, we use the term block diagram (or model) to refer to a time-based block diagram unless the context requires explicit distinction.

To summarize the meaning of time-based block diagrams: 1. Simulink block diagrams define time-based relationships between signals and state variables. The solution of a block diagram is obtained by evaluating these relationships over time, where time starts at a user specified " start time" and ends at a user specified " stop time. " Each evaluation of these relationships is referred to as a time step. 2. Signals represent quantities that change over time and are defined for all points in time between the block diagram's start and stop time. 3.

The relationships between signals and state variables are defined by a set of equations represented by blocks. Each block consists of a set of equations (block methods). These equations define a relationship between the input signals, output signals and the state variables. Inherent in the definition of an equation is the notion of parameters, which are the coefficients, found within the equation. It is possible to simulate a system manually, i. e. , to execute its model manually. However, this is unnecessary as the Simulink engine performs this task automatically on command from the user.

Simulating a dynamic system is a two-step process with Simulink. First, a user creates a block diagram, using the Simulink model editor that graphically depicts time-dependent mathematical relationships among the system's inputs, states, and outputs. The user then commands Simulink to simulate the system represented by the model from a specified start time to a specified stop time. Simulink provides a graphical editor that allows one to create and connect instances of block types (see Creating a Model) selected from libraries of block types (see Simulink Blocks) via a library browser.

Simulink provides libraries of blocks representing elementary systems that can be used building blocks. The blocks supplied with Simulink are called built-in blocks. Simulink users can also create their own block types and use the Simulink editor to create instances of them in a diagram. Customer-defined blocks are called custom blocks. 5. 2 About Blocks Blocks are the elements from which Simulink models are built. One can model virtually any dynamic system by creating and interconnecting blocks in appropriate ways. Simulink blocks fall into two basic categories: 1. . Nonvirtual blocks virtual blocks Nonvirtual blocks play an active role in the simulation of a system. If you add or remove a nonvirtual block, you change the model's behavior. Virtual blocks, by contrast, play no active role in the simulation; they help organize a model graphically. Some Simulink blocks are virtual in some circumstances and nonvirtual in others. Such blocks are called conditionally virtual blocks. Simulink defines signals as the outputs of dynamic systems represented by blocks in a Simulink diagram and by the diagram itself.

The lines in a block diagram represent mathematical relationships among the signals defined by the block diagram. For example, a line connecting the output of block A to the input of block B indicates that the signal output by B depends on the signal output by A. Blocks List 1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. Commonly Used ContinuousDiscontinuities Discrete Logic and Bit Operations Lookup Tables Math Operations Model Verification Model-Wide Utilities Ports & Subsystems Signal Attributes Signal Routing Sinks Sources User-Defined Functions Additional Math & Discrete The Simulink

Editor allows one to change the size, orientation, color, and label location of a block in a block diagram. All block names in a model must be unique and must contain at least one character. By default, block names appear below blocks whose ports are on the sides, and to the left of blocks whose ports are on the top and bottom, However we here discuss only the ones which are mostly used in the project. 5. 2. 1 Math Operations Table 5. 1 Math operation blocks BLOCK DESCRIPTION The Product block performs multiplication or division of its inputs. The Add block is an implementation of the Sum block.

The Gain block multiplies the input by a constant value (gain). The input and the gain can each be a scalar, vector, or matrix. The Sum block performs addition or subtraction on its inputs. This block can add or subtract scalar, vector, or matrix inputs. It can also collapse the elements of a single input vector. 5. 2. 2 Signal routing Table 5. 2 Signal routing blocks BLOCK DESCRIPTION The Demux block extracts the components of an input signal and outputs the components as separate signals. The block accepts either vector (1-D array) signals or bus signals.

The Mux block combines its inputs into a single output. An input can be a scalar, vector, or matrix signal. Depending on its inputs, the output of a Mux block is a vector or a composite signal, i. e. , a signal containing both matrix and vector elements The Switch block passes through the first (top) input or the third (bottom) input based on the value of the second (middle) input. The first and third inputs are called data inputs. The second input is called the control input. The Goto block passes its input to its corresponding From blocks.

The input can be a real- or complex-valued signal or vector of any data type. The From block accepts a signal from a corresponding Goto block, and then passes it as output. The data type of the output is the same as that of the input from the Goto block 5. 2. 3 Sinks Table 5. 3 Sink blocks BLOCK DESCRIPTION The Scope block displays its input with respect to simulation time. The Scope block can have multiple axes (one per port); all axes have a common time range with independent y-axes. The Display block shows the value of its input on its icon.

The Terminator block can be used to cap blocks whose output ports are not connected to other blocks. Using Terminator blocks to cap those blocks avoids warning messages. 5. 2. 4 Source Table 5. 4 Source blocks BLOCK DESCRIPTION Inport blocks are the links from outside a system into the system. The Constant block generates a real or complex constant value. The block generates scalar (1×1 2-D array), vector (1-D array), or matrix (2-D array) output, depending on the dimensionality of the Constant value parameter. The Sine Wave block provides a sinusoid.

The block can operate in either time-based or sample-based mode. The Step block provides a step between two definable levels at a specified time. If the simulation time is less than the Step time parameter value, the block’s output is the Initial value parameter value. For simulation time greater than or equal to the Step time, the output is the Final value parameter value. The Clock block outputs the current simulation time at each simulation step. This block is useful for other blocks that need the simulation time. 5. 2. 5 Ports and subsystems Table 5. Ports and subsystem blocks BLOCK DESCRIPTION A Subsystem block represents a subsystem of the system that contains it. The Subsystem block can represent a virtual subsystem or a true (atomic) subsystem The If block, along with If Action subsystems containing Action Port blocks, implements standard C-like if-else logic. The If Action Subsystem block is a Subsystem block that is preconfigured to serve as a starting point for creating a subsystem whose execution is triggered by an If block. Outport blocks are the links from a system to a destination outside the system. . 2. 6 Fuzzy logic tool box Table 5. 6 Fuzzy logic Tool box BLOCK DESCRIPTION The Fuzzy Logic Controller block implements a fuzzy inference system (FIS) in Simulink. The Fuzzy Logic Controller with Rule Viewer block implements a fuzzy inference system (FIS) with the rule viewer in Simulink. The details of the remaining blocks can be found in [5]. Output trajectories from Simulink can be plotted using one of three methods: 1. Feed a signal into either a Scope or an XY Graph block 2. 3. Write output to return variables and use MATLAB plotting commands. Write utput to the workspace using To Workspace blocks and plot the results using MATLAB plotting commands. 6. 1 Fuzzy Logic “ Fuzzy logic is all about the relative importance of precision: How important is it to be exactly right when a rough answer will do? ” [5]. Fuzzy logic is a fascinating area of research because it does a good job of trading off between significance and precision — something that humans have been managing for a very long time. Fuzzy logic is a convenient way to map an input space to an output space. A graphical example of an input-output map is shown in figure 6. 1. Fig 6. Example to illustrate fuzzy logic It’s all just a matter of mapping inputs to the appropriate outputs. Between the input and the output we’ll put a black box that does the work. What could go in the black box? Any number of things: fuzzy systems, linear systems, expert systems, neural networks, differential equations, interpolated multidimensional lookup tables, or even a spiritual advisor, just to name a few of the possible options. Clearly the list could go on and on. Of the dozens of ways to make the black box work, it turns out that fuzzy is often the very best way. Why should that be?

As Lotfi Zadeh, who is considered to be the father of fuzzy logic, once remarked: “ In almost every case you can build the same product without fuzzy logic, but fuzzy is faster and cheaper”. This is the starting point for everything else, and the great emphasis here is on the word “ convenient. ” The past few years have witnessed a rapid growth in the number and variety of applications of fuzzy logic. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection [5].

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalued logic. But in a wider sense, which is in predominant use today, fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of FL. What is important to recognize is that, even in its narrow sense, the agenda of fuzzy logic is very different both in spirit and substance from the agendas of traditional multi valued logical systems.

Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in AI, what is missing in such systems is machinery for dealing with fuzzy consequents and/or fuzzy antecedents. In fuzzy logic, this machinery is provided by what is called the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL). Although FDCL is not used explicitly in the Fuzzy Logic Toolbox, it is effectively one of its principal constituents.

In this connection, what is important to recognize is that in most of the applications of fuzzy logic, a fuzzy logic solution is in reality a translation of a human solution into FDCL [5]. On the other hand, the fuzzy system is based on some common sense statements. 6. 2 Fuzzy Logic process The point of fuzzy logic is to map an input space to an output space, and the primary mechanism for doing this is a list of if-then statements called rules. All rules are evaluated in parallel, and the order of the rules is unimportant. The rules themselves are useful because they refer to variables and the adjectives that describe those variables.

Before we can build a system that interprets rules, we have to define all the terms we plan on using and the adjectives that describe them. Fig 6. 2 Fuzzy Logic process 6. 3 Design of a Fuzzy Logic Controller According to [6], designing a fuzzy logic controller consists of the following four steps: 1) Fuzzification: In this step the crisp inputs are transformed to fuzzy values. 2) Rule design: In this step the fuzzy output truth values are calculated. 3) Computation: In this phase the required control actions are computed. 4) Defuzzification: In this step the fuzzy output is converted back to the crisp values.

The key steps involved in designing a fuzzy logic controller were examined [5]. They consist of, defining input and output variables, a knowledge base, fuzzy reasoning inference and a defuzzification procedure [6]. 6. 4 Foundation of Fuzzy Logic 6. 4. 1 Fuzzy Sets Fuzzy logic starts with the concept of a fuzzy set. A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership. To understand what a fuzzy set is, first consider what is meant by what we might call a classical set. A classical set is a container that wholly includes or wholly excludes any given element.

For example, the set of days of the week unquestionably includes Monday, Thursday, and Saturday. It just as unquestionably excludes butter, liberty, and dorsal fins, and so on. We call this set a classical set because it has been around for such a long time. It was Aristotle who first formulated the Law of the Excluded Middle, which says X must either be in set A or in set not-A [5]. Another version runs like this. Of any subject, one thing must be either asserted or denied. Most would agree that Saturday and Sunday belong, but what about Friday? It feels like a part of the weekend, but somehow it seems like it should be technically excluded.

Classical or normal sets wouldn’t tolerate this kind of thing. Either you’re in or you’re out. Human experience suggests something different, though: fence sitting is a part of life. Fuzzy reasoning becomes valuable exactly when we’re talking about how people really perceive the concept weekend as opposed to a simple-minded classification useful for accounting purposes only. More than anything else, the following statement lays the foundations for fuzzy logic. “ In fuzzy logic, the truth of any statement becomes a matter of degree”. Any statement can be fuzzy.

The tool that fuzzy reasoning gives is the ability to reply to a yes-no question with a not-quite-yes-or-no answer. This is the kind of thing that humans do all the time (think how rarely you get a straight answer to a seemingly simple question) but it is a rather new trick for computers. How does it work? Reasoning in fuzzy logic is just a matter of generalizing the familiar yes-no (Boolean) logic. If we give true the numerical value of 1 and false the numerical value of 0, we’re saying that fuzzy logic also permits in-between values like 0. 2 and 0. 7453. 6. 4. 2 Membership Functions

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse, a fancy name for a simple concept. Membership Functions in the Fuzzy Logic Toolbox The only condition a membership function must really satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape we can define as a function that suits us from the point of view of simplicity, convenience, speed, and efficiency. A classical set might be expressed as A = {x | x > 6}

A fuzzy set is an extension of a classical set. If X is the universe of discourse and its elements are denoted by x, then a fuzzy set A in X is defined as a set of ordered pairs. A = {x, µA(x) | x ? X} µA(x) is called the membership function (or MF) of x in A. The membership function maps each element of X to a membership value between 0 and 1. The Fuzzy Logic Toolbox includes 11 built-in membership function types. These 11 functions are, in turn, built from several basic functions: piecewise linear functions, the Gaussian distribution function, the sigmoid curve, and quadratic and cubic polynomial curves.

Fig 6. 3 Triangular and trapezoidal membership functions 6. 4. 3 Logical Operations Know let us see the term logic? The most important thing to realize about fuzzy logical reasoning is the fact that it is a superset of standard Boolean logic. In other words, if we keep the fuzzy values at their extremes of 1 (completely true), and 0 (completely false), standard logical operations will hold. As an example, consider the standard truth tables in figure 6. 4 Fig 6. 4 standard truth tables Now remembering that in fuzzy logic the truth of any statement is a matter of degree, how will these truth tables be altered?

The input values can be real numbers between 0 and 1. What function will preserve the results of the AND truth table (for example) and also extend to all real numbers between 0 and 1? One answer is the min operation. That is, resolve the statement A AND B, where A and B are limited to the range (0, 1), by using the function min (A, B). Using the same reasoning, we can replace the OR operation with the max function, so that A OR B becomes equivalent to max (A, B). Finally, the operation NOT A becomes equivalent to the operation 1-A. Notice how the truth table above is completely unchanged by this substitution.

Moreover, since there is a function behind the truth table rather than just the truth table itself, we can now consider values other than 1 and 0. Figure 6. 5 uses a graph to show the same information. We've converted the truth table to a plot of two fuzzy sets applied together to create one fuzzy set. The upper part of the figure displays plots corresponding to the two-valued truth tables above, while the lower part of the figure displays how the operations work over a continuously varying range of truth values A and B according to the fuzzy operations we've defined. Fi g 6. Graphical representation of Truth tables Typically most fuzzy logic applications make use of AND = min, OR = max, and NOT = additive complement operations and leave it at that. In general, however, these functions are arbitrary to a surprising degree. The Fuzzy Logic Toolbox uses the classical operator for the fuzzy complement as shown in the figure, but also enables you to customize the AND and OR operators [5]. 6. 4. 4 If-Then Rules Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. These if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic.

A single fuzzy if-then rule assumes the form if x is A then y is B where A and B are linguistic values defined by fuzzy sets on the ranges (universes of discourse) X and Y, respectively. The if-part of the rule " x is A" is called the antecedent or premise, while the then-part of the rule " y is B" is called the consequent or conclusion. An example of such a rule might be If service is good then tip is average Note that good is represented as a number between 0 and 1, and so the antecedent is an interpretation that returns a single number between 0 and 1.

On the other hand, average is represented as a fuzzy set, and so the consequent is an assignment that assigns the entire fuzzy set B to the output variable y. In the if-then rule, the word " is" gets used in two entirely different ways depending on whether it appears in the antecedent or the consequent. In general, the input to an if-then rule is the current value for the input variable (in this case, service) and the output is an entire fuzzy set (in this case, average). This set will later be defuzzified, assigning one value to the output.

Interpreting an if-then rule involves distinct parts: first evaluating the antecedent (which involves fuzzifying the input and applying any necessary fuzzy operators) and second applying that result to the consequent (known as implication). In the case of two-valued or binary logic, if-then rules don't present much difficulty. If the premise is true, then the conclusion is true. In general, one rule by itself doesn't do much good. What's needed are two or more rules that can play off one another. The output of each rule is a fuzzy set. The output fuzzy sets for each rule are then aggregated into a single output fuzzy set. . 5 Fuzzy Inference Systems Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. The process of fuzzy inference involves all of the pieces that are described in the previous sections: membership functions, fuzzy logic operators, and ifthen rules. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined.

The fuzzy inference diagram is the composite of all the smaller diagrams we've been looking at so far in this section. It simultaneously displays all parts of the fuzzy inference process we've examined. Information flows through the fuzzy inference diagram as shown in the figure 6. 6. Fig 6. 6 fuzzy inference diagram Notice how the flow proceeds up from the inputs in the lower left, then across each row, or rule, and then down the rule outputs to finish in the lower right. This is a very compact way of showing everything at once, from linguistic variable fuzzification all the way through defuzzification of the aggregate output. . 6 Defuzzification procedure Once the fuzzy output is computed, it must be defuzzified to a single value in the output universe of discourse z. The most popular method is centroid of area, defined as: Where μc(z) is the aggregated output membership function. Other defuzzification procedures can be found in [5]. Figures 6. 7, 6. 8 show the example of a two ruled system using max-min composition and max-product composition. The rule statements would be R1: IF X IS A1 AND Y IS B1, THEN Z IS C1 R2: IF X IS A2 AND Y IS B2, THEN Z IS C2 Fig 6. 7 max-min composition Fig 6. 8 max-product composition

For both composition styles the maximum is taken from each rule resulting in the specific area shown at the bottom of each figure. To get a crisp control output, the centroid of the final area is found using the previous defuzzification scheme [6]. 6. 7 Fuzzy Logic toolbox in MATLAB The Fuzzy Logic Toolbox is a collection of functions built on the MATLAB numeric computing environment. It provides tools for you to create and edit fuzzy inference systems within the framework of MATLAB, or if you prefer, you can integrate your fuzzy systems into simulations with Simulink.

You can even build stand-alone C programs that call on fuzzy systems you build with MATLAB. This toolbox relies heavily on graphical user interface (GUI) tools to help you accomplish your work, although you can work entirely from the command line if you prefer. The toolbox provides three categories of tools: 1. Command line functions 2. Graphical interactive tools 3. Simulink blocks The first category of tools is made up of functions that you can call from the command line or from your own applications. Many of these functions are MATLAB Mfiles, series of MATLAB statements that implement sp