FATCAR-AUV: Fault Tolerant Control Architecture of AUV

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Abstract - **Due to versatility, compact size, independence and covertness, Autonomous Underwater Vehicles are a highly valuable asset in the underwater battle space. Possible missions for Autonomous Underwater Vehicles (AUVs) range from dedicated and organic Mine Counter Measure (MCM), Rapid Environmental Assessment, and Special Operations to Reconnaissance, Surveillance and Intelligence. The wide range of possible applications and their partly contradictory nature calls for a complex control architecture, which consequently increases the possibility of components and systems failure, for which fault tolerant architecture is required. In this paper not only the hardware requirements of AUVs are mentioned (Section-I) but also the principles of Fault Tolerant Control System (Section-II) are extended, keeping in view the diverse and sundry requirement of AUVs. In the end the Reliability Block Diagram (RBD) analysis (Section-III) of the proposed architecture is presented which shows extend of fault tolerance incorporated by using this architecture.**

I HARDWARE REQUIREMENTS OF FATCAR-AUV

The FATCAR-AUV is equipped with following sensors [1,2]:

1.1 Multibeam Sonar

The multibeam sonar, also known as a "swathe bathymetry sonar", is a hydrographic survey tool consisting of a Mills Cross transducer array that produces multiple across-track beams as the intersection of one transmit beam (fan shaped across the survey track) with numerous receive beams (each fan shaped along the track). This allows the sounder to provide continuous swath bathymetry over a 120° to 150° sector.

1.2 Sidescan Sonar

The side scan sonar is one of the most accurate sensors for imaging large areas of the ocean floor. The side scan sonar transmits beams of acoustic energy from the side of the towfish and across the seabed. For these reasons, it is normally towed from ships. Unlike a ship, the AUV can operate close to the seabed, and consequently, the sonar transducers are mounted on the hull rather than towed.

1.3 Sub-bottom Profiler

The sub-bottom profiler is shallow geophysical sonar designed to provide higher resolution profiles below the seabed but with less penetration than lower frequency seismic equipment such as air guns and sparkers. Unlike these seismic devices which must tow separate hydrophone arrays for transmitting and receiving, the sub-bottom profiler is often self-contained in a single small towbody.

1.4 Conductivity Temperature and Depth (CTD) Sensor

A CTD Probe measures conductivity, temperature, and depth of the water. A large number of seawater parameters including salinity, density, and sound velocity can be computed from CTD data. Because the AUV speed is relatively slow and the CTD is contained within the AUVs free-flooding space, a pump is provided to flush water through the conductivity cell. This improves dynamic accuracy.

1.5 Propulsion

When an AUV is moving at constant speed, the thrust produced by the propeller is equal to the drag of the vehicle. That is,

$$\text{Thrust} = \text{Drag} = \frac{1}{2}\rho V^2 A C_D \tag{1}$$

where:
ρ= water density
A = reference area (often the projected frontal area)
V = speed
C_D = drag coefficient (propelled)

The power required for propulsion is the product of thrust and speed. Since, by the above equation, thrust is proportional to the speed *squared* (assuming that C_D remains more or less constant), power becomes proportional to speed *cubed*, that is,

$$\text{ThrustPower} = \text{Thrust} \times V = \frac{1}{2}\rho V^3 A C_D \tag{2}$$

Thrust power increases very quickly with speed. Doubling the speed requires eight times more power. Because the amount of energy the AUV can carry on-board is limited, the efficiency of the propulsion system is critical to minimize the amount of electrical power consumed. For optimum efficiency, the FATCAR-AUV is equipped with a single, two-bladed propeller mounted at the tail on the centerline and propulsion thrusters are using brushless dc motors.

1.6 Hydroplane Control

Most AUVs maneuver by means of deflecting control surfaces (hydroplanes). On the FATCAR-AUV, six independently actuated deflecting hydroplanes provide attitude control. The vehicle computer uses the hydroplanes for the closed-loop control of heading, pitch, roll and depth. The control system is designed such that, in the event of a hydroplane failure, the remaining ones can be re-tasked to compensate and the mission can be completed. This fault tolerant design enhances the overall reliability of the system. The hydroplane actuators utilize brushless DC motors in oil-filled, pressure compensated housings.

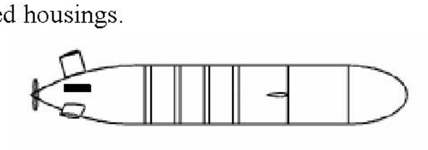


Fig. 1. Torpedo Body of FATCAR-AUV

1.7 Electric Power Distribution

Each device within the AUV is powered through its own isolated supply. Because the failure of one device or power supply will not affect other systems, reliability is increased. The FATCAR-AUV will use the Lithium Polymer batteries because of their high specific energy (130 Wh/Kg) and energy density (300 Wh/litre).

In estimating the total power requirement, the propulsion, payload and vehicle equipment requirements must all be taken into account. The following equation determines the energy capacity required to complete a mission of a given survey range, speed and depth:

$$\theta_t = \frac{p + p_p + p_v \ \ r}{3600v} \tag{3}$$

where:
e_t = energy carried in kWh
p_v = vehicle equipment power in Watts
p = propulsion power in Watts
r = survey range in km
p_p = survey sensor power in Watts
v = velocity in meters per second

To estimate the survey range given an energy capacity for different combinations of survey instruments the above equation can be solved for *r*, resulting in

$$r = \frac{3600\theta_t v}{p + p_p + p_v} \tag{4}$$

1.8 Vehicle Control Computer

Compact PCI is used for FATCAR-AUV because of its rugged standard format and the availability of low power processors and I/O components. The vehicle hardware is made up of a Pentium processor, digital and analog I/O boards, serial I/O, and Ethernet. A solid state hard drive will store software executables, mission plans, and vehicle data log files. All critical vehicle mission information (pitch, roll, position, speed, heading, depth, etc.) is logged to the hard drive during operation.

1.9 Locator & Emergency Equipment

At the end of a mission when the AUV returns to the surface, it must be located by the host surface ship (or other platform) and recovered. Because of waves, weather or darkness, it is prudent to equip the AUV with devices that make the task of locating it simple a GPS receiver is also mounted onboard FATCAR-AUV.

The FATCAR-AUV is designed with near neutral buoyancy with emergency weight drop mechanism for emergency recovery of AUV in case of fatal system error.

II FAULT TOLERANT CONTROL ARCHITECTURE OF AUV

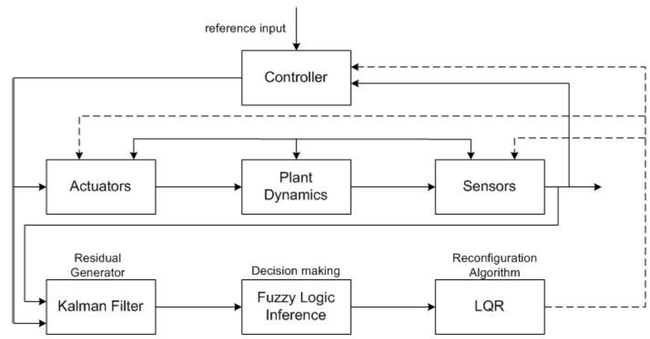


Fig. 2. Structure of Fault Tolerance Control Architecture [3] & [4]

2.1 Kalman Filter

The Kalman filter model assumes the true state at time *k* is evolved from the state at $(k-1)$ according to [5]

$$x_k = F_k x_{k-1} + B_k u_k + w_k \tag{5}$$

where
F_k = the state transition model which is applied to the previous state $\mathbf{x}_{k-1}$
B_k = the control-input model which is applied to the control vector u_k
w_k = the process noise which is assumed to be drawn from a zero mean multivariate normal distribution with covariance $\mathbf{Q}_k$.

$$w_k \sim N \ \ 0, Q_k \tag{6}$$

At time k an observation (or measurement) $\mathbf{z}_k$ of the true state $\mathbf{x}_k$ is made according to

$$z_k = H_k x_k + v_k \tag{7}$$

where H_k is the observation model which maps the true state space into the observed space and v_k is the observation noise which is assumed to be zero mean Gaussian white noise with covariance R_k.

$$v_k \sim N(0, R_k) \tag{8}$$

The initial state, and the noise vectors at each step $\{\mathbf{x}_0, \mathbf{w}_1, ..., \mathbf{w}_k, \mathbf{v}_1 ... \mathbf{v}_k\}$ are all assumed to be mutually independent.

2.2 Fuzzy Logic

General second order system equation is [6,7]

$$\ddot{x} = f(x, \dot{x}, t) + bu(t) \tag{9}$$

For b>0, $u(t)$ is input to the system.

The structure of controller is [8,9,10],

$$u = k\,\mathrm{sgn}(s) + u_{eq} \tag{10}$$

u_{eq} is called equivalent control.
k is maximal value of controller output which is constant.
s is called switching function
s is defined as:

$$s = \dot{e} + \lambda e \tag{11}$$

$$e = x - x_d \tag{12}$$

where
x_d is the desired state
λ is a constant
sgn (s) is a sign function and

$$sgn(s) = \begin{cases} -1 & if\ s < 0 \\ 1 & if\ s > 1 \end{cases} \tag{13}$$

After introducing boundary layer around the switch surface [11, 12]

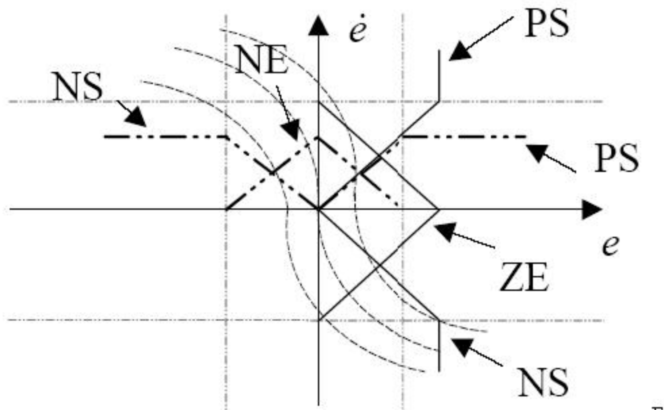
$$u = ksat\left(\frac{s}{\phi}\right) + u_{eq} \tag{14}$$

Whereas ϕ defines the thickness of the boundary layer sat (s/ϕ) is a saturation function and is defined as

$$sat\left(\frac{s}{\phi}\right) = \begin{cases} \dfrac{s}{\phi} & if\left|\dfrac{s}{\phi}\right| < 1 \\ \mathrm{sgn}\left(\dfrac{s}{\phi}\right) & if\left|\dfrac{s}{\phi}\right| > 1 \end{cases} \tag{15}$$

The i_{th} rule for a controller is expressed as follows:
If e is A_i and $\dot{e}$ is B_i then

$$u_i = ksat\left(\frac{\dot{e} + \lambda_i e - c_i}{\phi_i}\right) \tag{16}$$



Fi
3. Fuzzification of e and $\dot{e}$

The fuzzification of e and $\dot{e}$ is illustrated in Fig-3 above where λ_i and c_i are determined by open loop experimental data and ϕ_i will be determined by magnitude of oscillation

2.2.1 Heading Controller

A heading controller is designed for FATCAR-AUV. The input to the heading controller are heading error and heading error rate. The output is hydroplane deflection. Fig-4 below shows the fuzzy sets for the heading error.

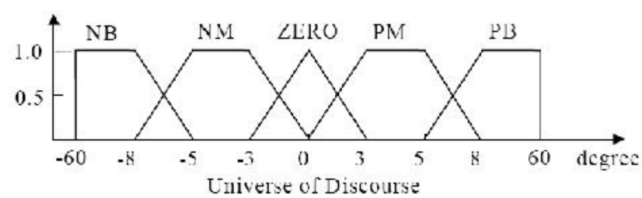


Fig. 4. Fuzzy Sets for Heading Error

There are no fuzzy sets for heading error rate. Table-1 shows the rule base of the heading controller.

TABLE 1 : RULES FOR FUZZY CONTROLLER

5 rules for fuzzycontroller of heading for FATCAR_AUV, k=20			
Antecedents	Output Function		
Heading error e	Thickness ϕ_i	Slope λ_i	Offset c_i
Positive Boundary	2.5	0.01	13.5
Positive Mean	3.0	1.50	1.0
ZERO	3.0	2.00	0.0
Negative Mean	3.0	1.50	-1.0
Negative Boundary	2.5	0.01	-13.5

Similar controllers are used for roll and pitch control of FATCAR-AUV.

2.3 LQR

For a discrete-time linear system described by [13]

$$x_{k+1} = Ax_k + Bu_k \tag{17}$$

with a performance index defined as

$$J = \sum_{k=0}^{\infty} \left(x_k^T Q x_k + u_k^T R u_k \right) \tag{18}$$

The optimal control sequence minimizing the performance index is given by

$$u_k = -Fx_k \tag{19}$$

where

$$\begin{aligned} F &= \tilde{R}^{-1} B^T P x_k \\ \tilde{R} &= R + B^T P B \end{aligned} \tag{20}$$

and P is the solution to the discrete Riccati algebraic equation

$$P = Q + A^T \left(P - PB \left(R + B^T P B \right)^{-1} B^T P \right) A \tag{21}$$

III RELIABILITY BLOCK DIAGRAM ANALYSIS

In this section the Reliability Block Diagram analysis of the proposed architecture (FATCAR-AUV) is presented in contrast to normal AUV architecture to show the reliability of the FATCAR-AUV [14, 15].

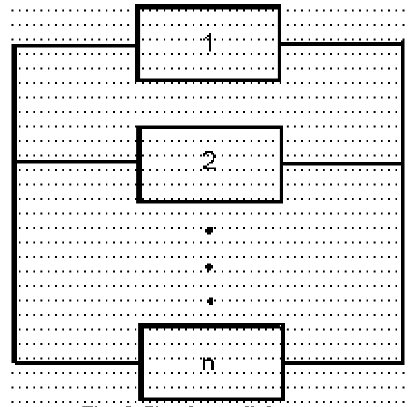


Fig. 5. Simple parallel system

3.1 Simple parallel system.

In a simple parallel system, probability of failure, or unreliability, for a system with n statistically independent parallel components is the probability that unit 1 fails *and* unit 2 fails *and* all of the other units in the system fail. So in a parallel system, all n units must fail for the system to fail. The unreliability of the system is then given by:

$$\begin{aligned} Q_s &= P\left(X_1 \cap X_2 \cap \ldots \cap X_n\right) \\ &= P(X_1)\, P(X_2 \mid X_1)\, P(X_3 \mid X_1 X_2) \ldots P(X_n \mid X_1 X_2 \ldots X_{n-1}) \end{aligned} \tag{22}$$

where:
Q_s = unreliability of the system.
X_i = event of failure of unit i.
$P(X_i)$ = probability of failure of unit i.

3.2 Reliability of k-out-of-n Independent and Identical Components

The simplest case of components in a k-out-of-n configuration is when the components are independent and identical. In other words, all the components have the same failure distribution and whenever a failure occurs, the remaining components are not affected. In this case, the reliability of the system with such a configuration can be evaluated using the binomial distribution, or:

$$R_s(k, n, R) = \sum_{r=k}^{n} \binom{n}{r} R^r (1-R)^{n-r} \tag{23}$$

Where:
n= the total number of units in parallel.
k = the minimum number of units required for system success.
R = the reliability of each unit.

3.3 Series Systems

In a series configuration, reliability of the system is the probability that unit 1 succeeds and unit 2 succeeds *and* all of the other units in the system succeed. So, all n units must succeed for the system to succeed. The reliability of the system is then given by:

$$R_s = P(X_1 \cap X_2 \cap \ldots \cap X_n)$$
$$P(X_1)\,P(X_2 \mid X_1)\,P(X_3 \mid X_1 X_2) \ldots P(X_n \mid X_1 X_2 \ldots X_{n-1}) \quad (24)$$

Where:

R_S = reliability of the system.
X_i = event of unit i being operational.
$P(X_i)$ = probability that unit i is operational.

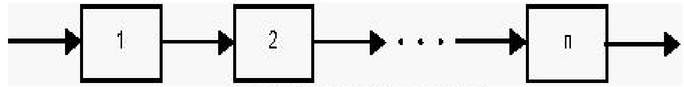


Fig. 6. Simple Series Systems

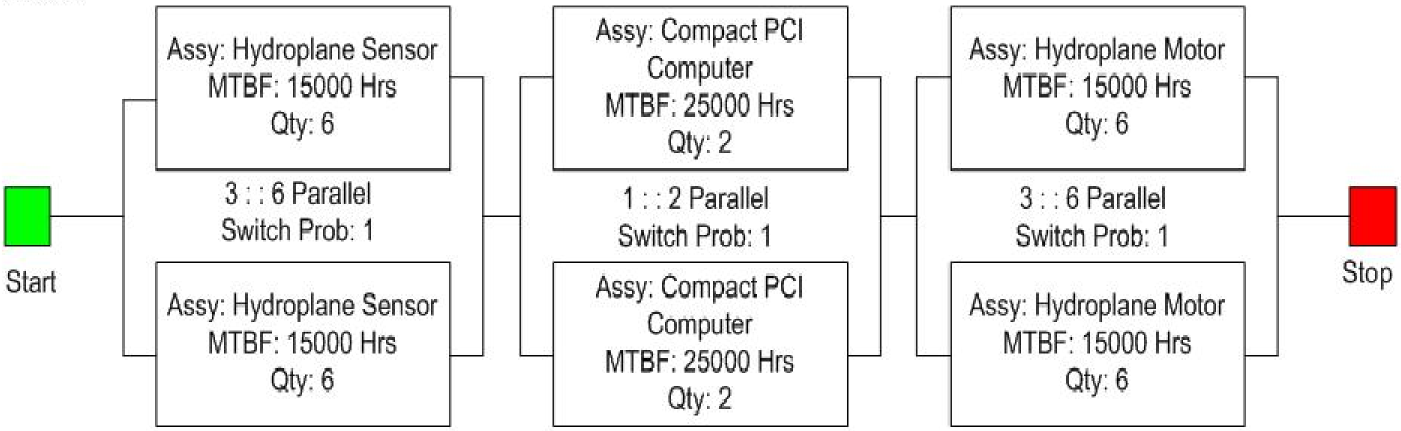


Fig. 7. Reliability Block Diagram of FATCAR-AUV

3.4 FATCAR-AUV RBD

RBD of FATCAR-AUV has 6 Hydroplane Sensors connected in parallel and 3 are essentially required, similarly 2 Compact PCI Computers and 6 Hydroplane Motors are connected as shown in Fig-5 above [16-20]. In the analysis it is assumed that switching probability is 1. The results of above simplified RBD of FATCAR-AUV for the first 10,000 hours are shown below in contrast the doted line shows the results of AUV without proposed fault tolerance architecture. All the functions are plotted with reference to time.

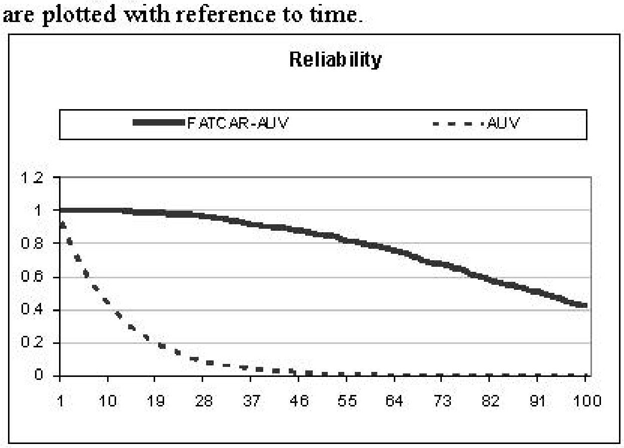


Fig. 8. Reliability vs. Time

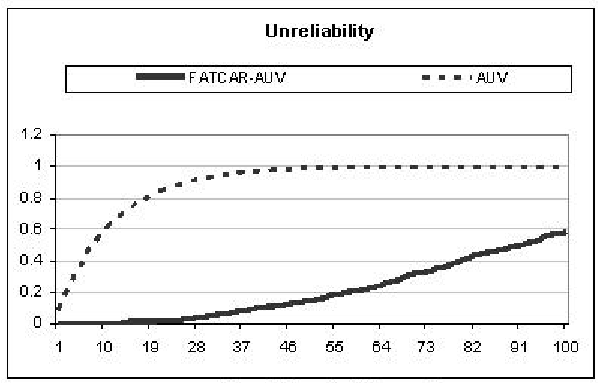


Fig. 9. Unreliability vs. Time

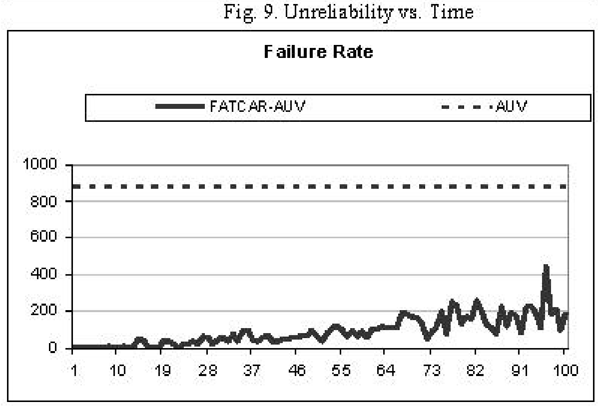


Fig. 10. Failure Rate vs. Time

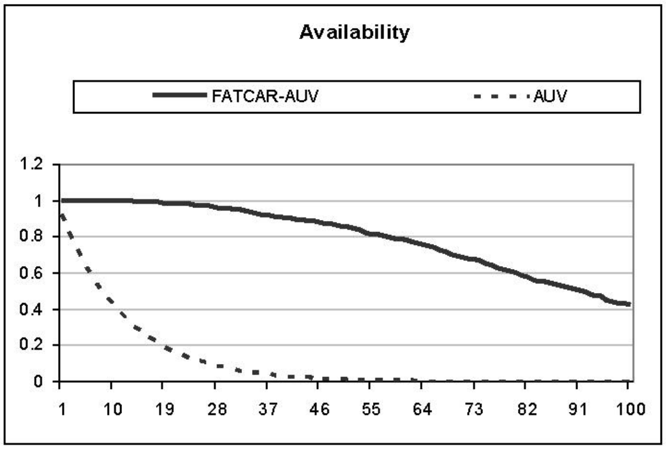


Fig. 11 Availability vs. Time

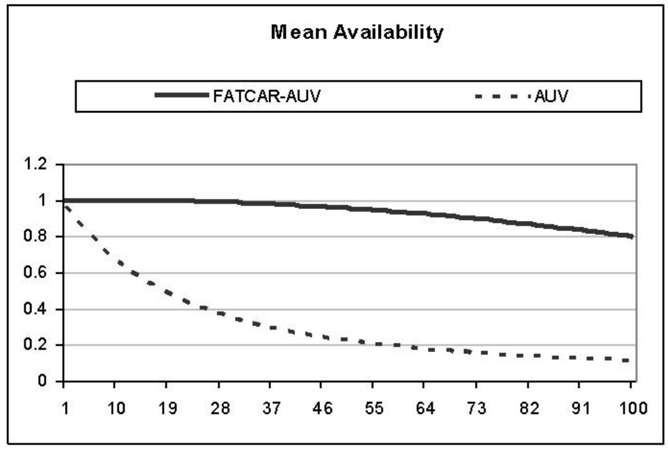


Fig. 14 Mean Availability vs. Time

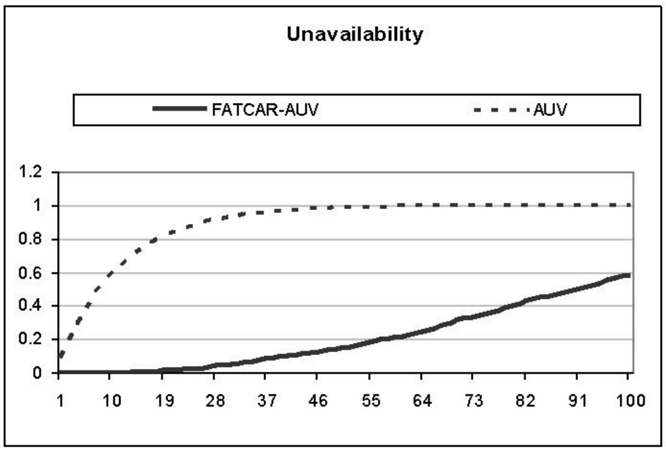


Fig. 12 Unavailability vs. Time

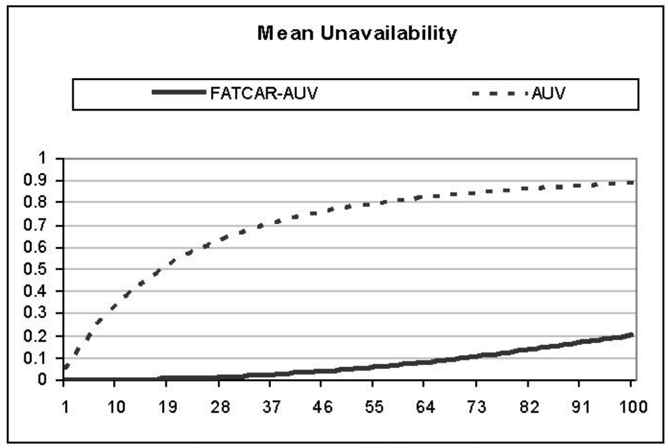


Fig. 15 Mean Unavailability vs. Time

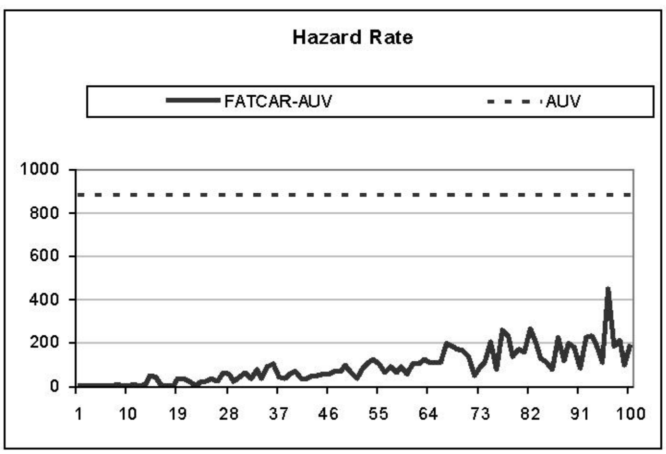


Fig. 13 Hazard Rate vs. Time

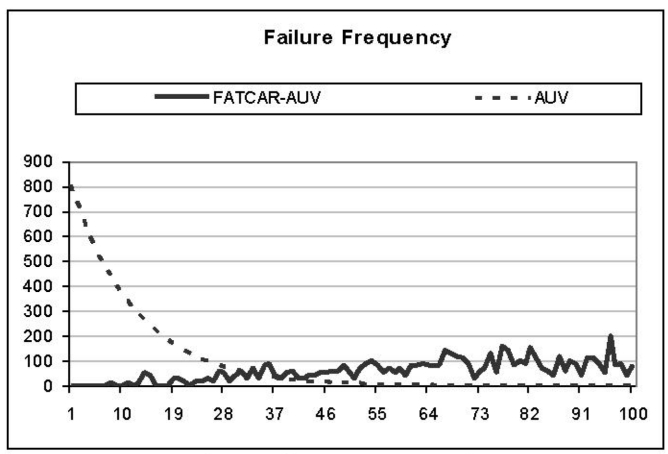


Fig. 16 Failure Frequency vs. Time

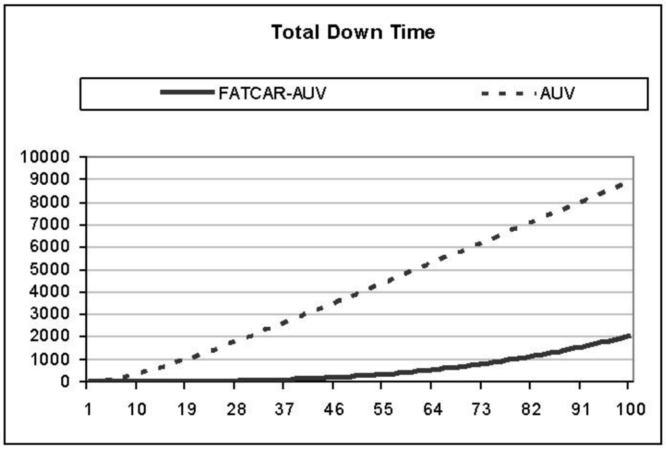


Fig. 17 Total Down Time vs. Time

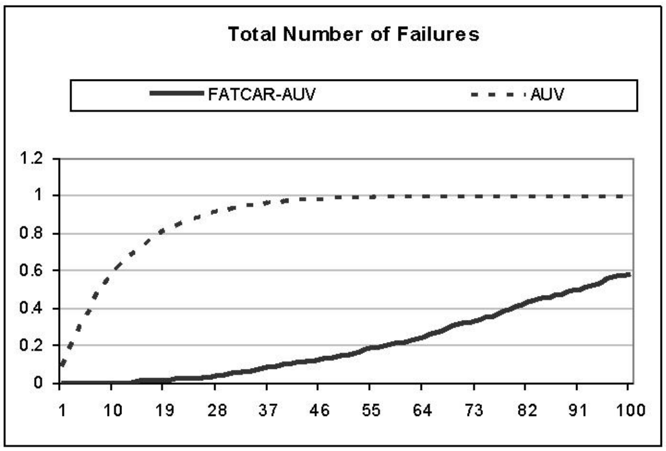


Fig. 18 Total Number of Failures vs. Time

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