

Analysis of Health and Usage Monitoring System (HUMS) Users' Perspective towards Mission Benefits Using Regression Analysis

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ABSTRACT

Mission benefits are seen as an important indicator of overall effectiveness of Condition-Based Maintenance (CBM) implementation. This creates incentives for Army personnel at all levels to adopt CBM. The research approach presents a step in the direction of better understanding of how mission benefit areas like morale, sense of safety etc. are influenced by perspective of army personnel who fly and maintain Blackhawk, Kiowa, Chinook and Apache helicopters around the world equipped with Health and Usage Monitoring Systems (HUMS). The study also investigates if this attitude can be described by a linear regression model. Response data collected from seventy-six helicopter personnel was analyzed to determine whether regression analysis can describe the users' attitude towards different aspects of benefits. When cross validation was performed, the multiple linear regression model was able to predict performance response with a correlation coefficient as high as 0.95.

INTRODUCTION

A Health and Usage Monitoring Systems (HUMS) is a sensor-based real-time diagnostic system which collects data from numerous critical points of mechanical structure such as engines, rotors, gearboxes and drive shafts and processes the data using a predefined algorithm. The results provide information to flight and maintenance crews. Based on the provided information, decisions are taken for performing maintenance actions. HUMS is closely related to the implementation of Condition-Based Maintenance (CBM) and plays an important role to the adoption of CBM instead of preventive and/or reactive maintenance. The aim of this paper is to analyze how the flight and maintenance crews accept this new concept of maintenance and to understand how their attitude towards performance gets influenced by other attitude factors.

HUMS refers to any onboard vibration monitoring system including vibration monitoring unit (VMU), vibration measurement enhancement program (VMEP), modernized signal processing unit (MSPU), Integrated Mechanical Diagnostics - Health and Usage Management System (IMD-HUMS), Integrated Vehicle Health Management - Health and Usage Management System (IVHM-HUMS) etc. Implementation of HUMS is one of the key factors that

helps the practice move from traditional to predictive maintenance. It has been seen that many predictive maintenance program failed to generate measurable benefits after implementation. These failures were not related to technical limitations but rather they were unable to make the necessary changes in the work place to adopt new practices which would allow maximum utilization of predictive tools that have been introduced [1]. Personnel often do not understand the sheer need for a change to better, more effective practice and are reluctant to voluntarily welcome new technology. To resolve this issue, a group of people from the current workforce are trained to ensure maximum return on investment as further adaptation depends upon their performance. For this reason it is necessary to understand the attitude of flight and maintenance crews towards different aspects of mission benefits like performance, morale, operational readiness, sense of safety and sense of time savings.

Studies have been carried out measuring HUMS effectiveness in deployment both in rotorcraft and land vehicles [2, 3]. These studies are mostly focused into design and capability assessment, measuring economic feasibility of implementation [4]. Fraser recommended in favor of using HUMS in military helicopter fleets as adopting this technology would be economically beneficial for over 75% rotorcraft of the fleets [5]. Bayoumi et al. analyzed surveyed responses of personnel from different establishment. The chief finding was to highlight non-tangible benefits such availability, morale, safety, mission aborts etc. and their improvements [6]. In this research study, efforts are taken to address the relation among mission benefit areas, so that for

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future adaptation of HUMS, authority may make decisions more easily based on a user survey of a few questions.

MAIN BODY

HUMS deployment on AH-64A (Apache) aircraft

HUMS is a sensor-based diagnostic system which has a broad range of application starting from the offshore oil and gas industry to business jets, drones, fixed wings aircrafts and military aircrafts etc. [7]. Over the past twenty years, the US army has been actively installing and utilizing onboard HUMS for its fleet of Apache, Blackhawk, Chinook, Kiowa helicopters.

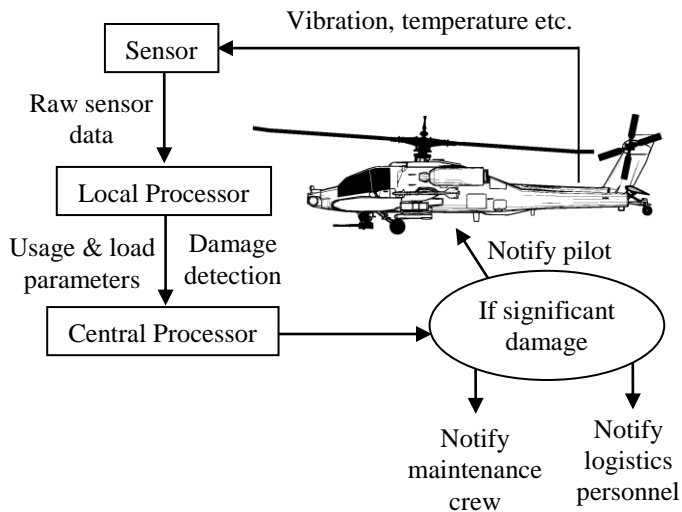


Figure 1. A schematic diagram of a HUMS architecture for structural application.

The primary concern of HUMS is to enable aircraft to monitor the health of rotary components of a mechanical system and perform condition monitoring of critical components in the drive train. HUMS continuously records structural and transmission usage, transmission vibrations, rotor track and balance information, and engine power assurance data. Besides usage and event analysis, it also records parametric data from the aircraft's bus. HUMS collects speed, torque, pressure and temperature data as well as vibration, rotor track and balance data from a number of sensors instrumented on critical areas of the structure. Sensors are linked to processors using pre-defined algorithms that perform health assessment and evaluate the criticality for a particular component. This information is displayed to the pilot and also is saved for future use by maintenance and logistic personnel. AH-64A and D aircrafts at South Carolina Army National Guard (SCARNG) from which The Army Maintenance Management System-Aviation (TAMMS-A) data has been collected are equipped with a MSPU. The AH-64A installment of this HUMS device implements 18 accelerometers and 3 tachometers for vibration and usage sensing. The accelerometers are located throughout the aircraft, particularly where vibration is a

known problem for the AH-64, such as tail rotor drive train (TRDT) components.

Mission benefits

Benefits achieved from HUMS deployment on aircrafts can be split into two categories; basic and mission. These are important in measuring economic effectiveness of CBM using a cost-benefit model. Basic benefits are tangible and are quantifiable by means of reduced flight hour cost, operating cost, HUMS investment cost, test flight cost etc. Mission benefits are the soft benefit areas which consist of operational readiness, morale, performance, sense of safety and sense of time savings. These information can be attained through measuring attitudes. A common way to assess person's attitude towards something is to take a survey.

Attitude measurement & Likert scale

An attitude can be described as a person's evaluation and feeling towards some object or event, which in turn may affect a person's behavior. Human response is a dynamic process, guided by certain cognitive and behavioral rules, and influenced by physical and psychological factors like memory, knowledge, emotions etc. According to social psychologists attitude is comprised of three major components; cognitive, affective and behavioral [8]. Knowledge or belief of a person is represented by the cognitive component. The feeling that is produced by the object or event is the affective component of attitude. The behavioral component is a pre-disposition to act toward the object in a particular way. Besides these three components, attitude has two important aspects. One is direction which can be positive or negative and another is intensity which represents strength of feelings, which can be strong or weak. Among many methods, a Likert scale is an attitude scale, which can be tested for reliability assessment of the individual or collective item. This reliability assessment might use the correlation between individual or aggregated items score [9].

The Likert scale is the mostly used method for attitude measurement as it is easy to understand and respond to. Dr. Rensis Likert, a sociologist at the University of Michigan, developed this technique back in 1932 as a means of measuring psychological attitude in a scientific way. Originally five response choices were proposed ranging from *strongly disapprove* to *strongly approve*. The number of response options in scales usually vary from five to seven. The scale uses agree-disagree format which contains information on both direction and intensity. Studies show that five or seven point scales are advantageous for obtaining responses to survey questions. Since they allow for the discrimination of both the direction and intensity; and they permit a neutral or middle response [10]. The individual or aggregated responses are used to establish correlation between quantitative variables.

This research attempt also takes initiative to explore any relationship present between performance attitude and

remaining variables and if present, to express that relation using multiple linear regression analysis techniques and to cross validate that relation.

The regression model is a statistical technique to explore the quantitative relationship between an explanatory variable and response variable. In most of the cases, a linear function is assumed. If the linear function does not fit the data properly, non-linear functions might be used.

Concept

Condition-based maintenance is an information based maintenance technique which is applicable on any mechanical system and components. By using the data from actual operating condition of the system components, CBM optimizes system operation by maximizing the interval between repairs and minimizing the number and costs of unscheduled repairs and downtime. Since 1998 the University of South Carolina (USC) and the South Carolina Army National Guard (SCARNG) have engaged in a number of research programs focusing on CBM for US Army Aviation equipment, especially Army Rotorcraft. Those researches were aimed at reducing Army Aviation maintenance costs, reducing the maintenance burdens on soldiers and improving equipment availability. USC’s previous efforts focused on the measurement of maintenance test flights (MTFs), part costs and the percentage of unscheduled maintenance occurrences as well as identification of various intangible benefits like safety, performance, morale, operational readiness etc. [6, 11].

Assumption

A few assumptions were made for the experiment conducted:

1. Individuals who participated in the survey have both ability and motivation to report attitudes.
2. Observations are assumed to be independent.
3. Variables i.e. operational readiness, morale, performance, sense of safety and sense of time savings; have a normal distribution.
4. The difference between any two consecutive alternatives are assumed to be same and uniform. For example, the difference between “Strongly Agree” and “Agree” is same as that of between “Agree” and “Neutral”.

Method

USC’s research team, crew chiefs and pilots created a set of questions designed to address aspects of mission benefits areas; operational readiness, morale, performance, sense of safety and sense of time savings as they are related to operating and maintaining Blackhawk, Apache etc. helicopters. Finally a Likert scale based questionnaire was created to use in surveying various units in the National Guard and Regular Army who had experience in using HUMS. Over the time spanning March 2010 to April 2011, seventy six helicopter personnel took this survey. The survey questionnaire has twenty-five questions and participants

responded to them using six alternatives; Strongly Agree (5), Agree (4), Neutral (3), Disagree (2), Strongly Disagree (1) and I Don’t Know (0).

Twenty-five survey questions were categorized into five groups based on the benefits area they were focused on; which are operational readiness, morale, performance, sense of safety and sense of time savings. Eight of twenty-five questions of the survey were focused on performance, four were on operational readiness, six belong to morale, three to sense of safety and four to sense of time savings. Table 1 shows some of the grouped questions with corresponding benefit areas.

Table 1. Sample question from the survey questionnaire

Benefit area	Corresponding survey questions
Performance	<ul style="list-style-type: none"> ➤ HUMS enhances our ability to reliably detect impending component failure and problems. ➤ HUMS enhances the troubleshooting process.
Operational readiness	<ul style="list-style-type: none"> ➤ HUMS results in less frequent mission aborts due to maintenance. ➤ HUMS improves operational availability.
Morale	<ul style="list-style-type: none"> ➤ HUMS improves the overall maintenance decision making process. ➤ Having HUMS on the aircraft increases my confidence.
Sense of safety	<ul style="list-style-type: none"> ➤ There is a greater margin of safety with HUMS on the aircraft.
Sense of time savings	<ul style="list-style-type: none"> ➤ HUMS reduces the lead time for obtaining components that need service. ➤ HUMS reduces component change frequency.

In this research approach, average of response scores from flight and maintenance crews are aggregated based on the focus area. Correlation was checked first by plotting a scatter diagram and then influence of other particular mission benefits on users’ performance is investigated. In this research work, it is assumed that the functional relationship between variables is linear.

During the analysis, 80% of the sample data was used as training set for model building and 20% as the testing set. Before proposing a MLR model, regression assumptions were checked using scatter plot, residual vs predicted plot, residual vs time plot and normal plot. The scatter plot provides an initial check of the linearity assumptions for regression. In the scatter plots, each explanatory variable was paired with the response variable, performance and the presence of linearly increasing or decreasing trend with

constant noise was looked for. For example the average response for performance was plotted against that of morale, where each data point represents response from each survey participant. As eight of twenty-five questions of the survey were focused on performance, the aggregated score for performance ranges from 0 to 40, and average ranges from 0 to 5. Similarly aggregated score for six morale based response ranges from 0 to 30, and average six ranges from 0 to 5.

By careful observation of residuals plots, the assumptions can be assessed in more detail. Commonly, the residuals are plotted against the predicted value estimated using the fitted regression function. Evenly scattered residuals around the zero line along the range of predicted values indicate the linear relationship with constant variability of residuals with predicted values. The residual vs time plot represents the distribution of residuals with the number of observation in sample used for regression. Any presence of pattern, violates the assumption that the model was correctly specified. Normal Q-Q plot of residuals is the plot of residuals against the values they would be expected to take if they come from a standard normal distribution.

After checking assumptions, a valid multiple linear regression (MLR) model was proposed to relate the attitude towards performance to a set of 4 variables; attitude towards operational readiness, morale, sense of safety and sense of time savings. Here, performance was considered as the response variable and the remaining four were explanatory variables. The aim of proposing a model was to observe the individual influence of variables on performance and also to arrive at a conserving sub-model of variables that still well explains performance. Test data was then plugged into the obtained regression model and the model accuracy was measured.

Model selection criteria

Multiple linear regression (MLR) relates a number of explanatory variables with a response variable. When collinearity is present among the explanatory variables, it is hard to understand their individual influence on response variable. To avoid collinearity, explanatory variables are needed to be chosen with care based on a number of criteria such as:

1. Coefficient of determination,

$$R^2 = [SS(\text{Total}) - SS(\text{Residual})] / SS(\text{Total}) \quad (1)$$
 R^2 value ranges from 0 to 1 and model was chosen with high R^2 value.
2. Root mean square error,

$$RMSE = \sqrt{[SS(\text{Residual}) / (n - (k+1))]} \quad (2)$$
 Model was chosen with minimum RMSE.
3. Mallows' C_p ,

$$C_p = [SS(\text{Residual})_p / ME(\text{Residual})_p] - (n - 2p) \quad (3)$$
 Model was chosen for the smallest p such that $C_p \approx p$.

4. Akaike's information criterion,

$$AIC = n * \log [SS(\text{Residual})/n] + 2p \quad (4)$$
 Model with smallest AIC was chosen where AIC can be negative.
5. Schwarz' Bayesian Information criterion,

$$SBC = n * \log [SS(\text{Residual})/n] + p * \log(n) \quad (5)$$
 Model with smallest SBC was chosen where SBC can be negative.

RESULT AND ANALYSIS

The assumptions for multiple linear regression were checked first from scatter plot. In figure 2, four scatter plots are presented where positive linear increasing pattern with constant noise was observed. This indicates a positive linear correlation between the variables supporting the first assumption of regression. For example the average response for performance was plotted against that of morale, where each data point represents average score of responses from each survey participant (figure 2a).

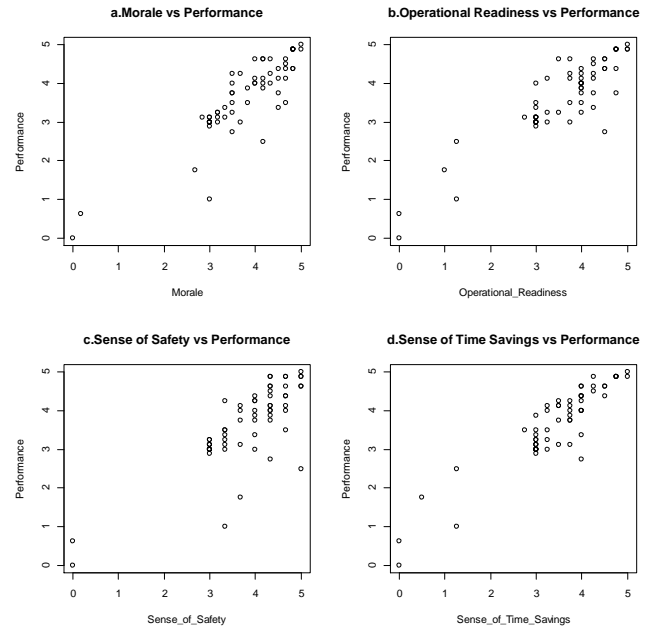


Figure 2. Scatter plots of performance against explanatory variables suggest that the variability in performance increases with corresponding variables.

After that residuals plotted against predicted value and the number of observation were observed to have a close look at the assumptions. From figure 3a it is visible that the residuals are mostly scattered around the zero line if extreme values are overlooked. In the residuals plot against the number of observation in figure 3b, no pattern was visible which supports the assumption of uncorrelated error with number of observation. The mild left skewed distribution of residuals is evident from the histogram (figure 3c) which supports the normality and gives indication of probable outliers. The assumption of normality of residuals seems appropriate from the nearly linear Normal Q-Q plot in figure

3d. However, in the Shapiro-Wilk normality test p-value (8.518e-5) is less than 0.01, which rejects the null hypothesis of normality.

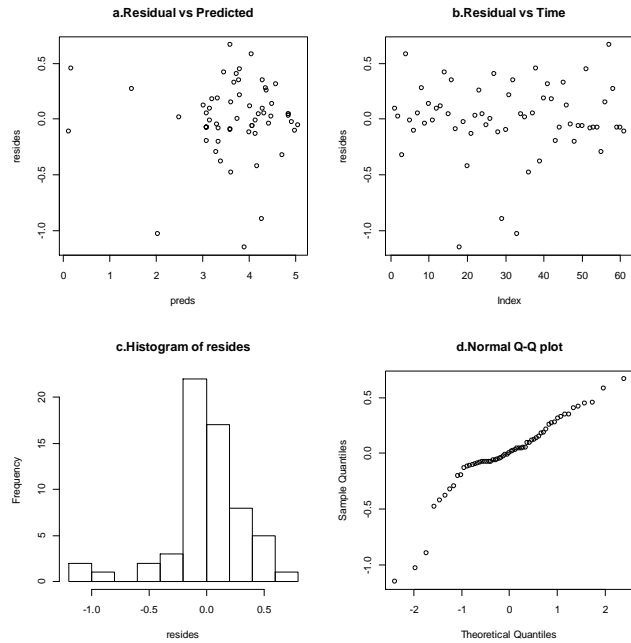


Figure 3. Check of assumptions of regression model for performance against remaining variables.

The fitted regression line was:

$$Performance = 0.10632 + 0.39024 * Morale + 0.05977 * Operational\ readiness + 9.377e-5 * Sense\ of\ safety + 0.53909 * Sense\ of\ time\ savings \quad (6)$$

The null hypothesis can be tested to investigate whether any strong evidence is present in the data that explains the effect of explanatory variables on the mean response for performance. The null hypothesis statement is; the mean performance response does not change with the response of morale, operational readiness, sense of safety or sense of time savings; while the alternative statement was at least one of the coefficients is nonzero. This can be expressed as

Null hypothesis, H_0 :

$$\beta_{morale} = \beta_{operational\ readiness} = \beta_{sense\ of\ safety} = \beta_{sense\ of\ time\ savings} = 0$$

And alternate hypothesis, H_a :

$$\beta_{morale} \neq 0 \text{ or } \beta_{operational\ readiness} \neq 0 \text{ or } \beta_{sense\ of\ safety} \neq 0 \text{ or } \beta_{sense\ of\ time\ savings} \neq 0$$

During hypothesis test, the test statistics are compared with the t-distribution on n-5 (i.e. sample size – regression coefficient) degrees of freedom. Table 2 shows that the two-tailed P-value for morale and sense of time savings is less than 0.01. This proves strong evidence for rejecting the null hypothesis that the mean response for performance does not change with the moral or sense of time savings response, while rest of the variables remain constant. However, we cannot reject the null hypothesis for operational readiness

and sense of safety as the P-value is greater than 0.15. This analysis indicates the strong influence of two specific mission benefit areas on the users' perspective towards performance. The regression analysis output is summarized in table 2.

Table 2. Regression parameter estimates for performance and remaining variables

Coefficient	Parameter estimate, β	t	P	VIF
Intercept	0.10632	0.58	0.5622	0
Morale	0.39024	2.67	0.0098	10.27
Operational readiness	0.05977	0.50	0.6209	8.93
Sense of safety	9.377e-5	0.001	0.9994	6.93
Sense of time savings	0.53909	4.60	0.0001	7.86

Presence of collinearity among explanatory variables might make it hard to find the predictive effect of each one on performance. Collinearity can be estimated from variance inflation factor (VIF). When the value of VIF exceeds 10, this indicates a strong evidence of collinearity in the explanatory variables. From table 2 it is observed that all the variables have collinearity. Morale is the one with severe collinearity.

By selecting explanatory variable wisely, the variable with most predictive effect on response variable can be estimated. This can be done using the following some model selection criteria (R^2 , RMSE, C_p , AIC, SBC). From the summary of analysis, it is observed that three of the selection criteria among five choose two particular variables, which are morale and sense of time savings. This supports the result of hypothesis test achieved from earlier estimation. The model selection analysis is summarized in table 3.

Table 3. Explanatory variable selection for MLR model

Selection criteria	Cut off value	Variables in model
R^2	0.90	All variables
RMSE	0.34	Morale, Sense of time savings
C_p	5.00	All variables
AIC	-130.13	Morale, Sense of time savings
SBC	-119.96	Morale, Operational readiness and Sense of time savings

Using equation 6, performance response was predicted based on observed response of remaining variables using training set data. The predicted and observed performance response had a correlation coefficient, r of 0.95. Commonly the value of r ranges from -1 to +1, indicating negative strong response to positive strong response. The correlation

coefficient of 0.95 indicates that the predicted performance response using the MLR model is very close to the observed response.

CONCLUSIONS

USC's attempt for better understanding of HUMS users' perspective involves using a Likert scale survey questionnaire and analysis of survey participants' attitude towards mission benefits that is, intangible benefits. By analyzing the response collected from a group flight and maintenance crews, who have used HUMS, it can be concluded that the attitude towards performance is mostly influenced by two factors, one is users' attitude towards how HUMS helps to increase their morale. And the other is sense of time savings formed in the users' mind by using HUMS. These two factors strongly correlate with the attitude towards performance. As a result, when users think that HUMS is increasing their confidence during maintenance action and during flight and also helping to save time in maintenance, their attitude is found to be inclined towards performance improvement. This will help the authority taking decisions in favor of HUMS deployment in broader scale knowing the users' feedback.

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