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# Preventive Maintenance of Autonomous Control Systems based on Remaining Useful Life

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**ABSTRACT:**

The remaining useful life (RUL) estimation is essential for the preventive maintenance of autonomous control systems which are expected to perform well without human guidance under significant uncertainties in the system and environment. This paper presents a new method to estimate the RUL of the electronic control board in an autonomous control system. The proposed method belongs to the life consumption monitoring approach. Conventional life consumption methods are based on physics-of-failure models, and depends on the deterministic nature of system failures expressed through failure models. However, practically, it is extremely difficult to construct a physics-of-failure model. Unlike conventional life consumption methods, the proposed RUL estimation method does not rely on physics-of-failure models, and computes the RUL by using a standard procedure for the reliability prediction. The proposed method consists of four major steps: 1) identification of environmental factors, 2) extraction of all feasible environmental conditions, 3) computation of a failure rate for each feasible environmental condition, and 4) RUL estimation considering the history of environmental stresses. The proposed RUL estimation method is essential to the preventive maintenance process, which can be tactical (i.e., real time interpretation and feedback) or strategic (i.e., maintenance planning). For demonstration, the proposed method has been applied for the RUL estimation of an autonomous traffic signal controller.

**Keywords:** Autonomous control system, life consumption method, maintenance planning, preventive maintenance, remaining useful life.

## I. INTRODUCTION

Autonomous control systems are designed to perform well without human guidance under significant uncertainties in the system and environment for extended periods of time, and they include unmanned surface vehicles, autonomous aerial vehicles, and autonomous traffic signal controllers, as shown in Fig. 1. In the case of autonomous control systems, the service providers are responsible for maintaining equipment performance. Since the unexpected failure of an autonomous control system may cause serious damages, it is very important to have a preventive maintenance polices that maximize availability or minimize life cycle costs [1-3]. The maintenance tasks can be preventive maintenance or repairs when equipment fails which are closely related to the life cycle costs. For this reason, the service providers are often faced with the conflicting objectives of maintaining a high level of equipment availability and holding down costs. If it is possible to estimate the remaining useful life (RUL) of the electronic control board in an autonomous control system, it would be very useful to the maintenance decision making process. Prognostics is the estimation of RUL, and it is essential to establish an effective maintenance plan.


(a) Unmanned surface vehicle (b) Autonomous aerial vehicle

(c) Autonomous traffic control system

**Fig 1.** Autonomous control systems and electronic control boards

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Existing prognostics and health management (PHM) methods to evaluate a product's health (i.e., RUL) can be classified into two categories: the condition monitoring methods [4-6] and life consumption monitoring methods [7-10]. The condition monitoring methods forecast RUL based on precursor variable monitoring. They do not require system failures to be deterministic in nature, but do require that the chosen precursor has a deterministic link to the health (i.e., RUL) of the actual system [11]. The life consumption monitoring methods are based on physics-of-failure models. They depend on the deterministic nature of system failures expressed through failure models. Most of the physics-of-failure models compute accumulated damage and thereby forecast RUL by considering a history of environmental stresses, such as temperature, humidity, vibration, and radiation [7].

The objective of this paper is to develop a new method to estimate the RUL of the electronic control board which is the most important part of an autonomous control system. The proposed method belongs to the life consumption monitoring methods. Most of previous research results [7-10] are based on the physics-of-failure models. Once the physics-of-failure model is acquired, it is possible to assess the RUL with high accuracy. As depicted by many researchers [7-10], the physics-of-failure model, however, requires a thorough understanding of the structure and life cycle conditions of the target system and its failure modes and mechanisms. Practically, it is very difficult to construct a physics-of-failure model, and to prove the fidelity of the model. To avoid the difficulty, a new RUL estimation method which does not rely on the physics-of-failure models is proposed in this paper. The proposed method computes the RUL by using a standard procedure for the reliability prediction 'MIL-HDBK-217F' [12]. The first standard procedure for the reliability prediction was MH-217 which was published by the US Navy in 1962. While MH-217 were updated several times, other agencies were developing various reliability prediction models including Bellcore RPP, NTT Procedure, British Telecom HRD4, CNET Procedure, and Siemens Procedure [12-15].

The overall structure of this paper is as follows. Section II addresses the overall approach to the development of a new RUL estimation method, and a detailed description of the proposed method. To show the applicability of the proposed method, a demonstration is given in Section III. Finally, some concluding remarks are provided in Section IV.

## II. RUL ESTIMATION WITHOUT PHYSICS-OF-FAILURE MODEL

As mentioned earlier, the objective of this study is to develop a new method to estimate the RUL of the electronic control board used in an autonomous control system. Since most of autonomous control systems are operated outdoors, the RUL of the electronic control board is significantly affected by the environmental conditions. Conventional life consumption monitoring methods [7-10] are based on physics-of-failure models. In general, physics-of-failure models compute accumulated damage and thereby forecast RUL by considering a history of environmental stresses, such as temperature, salinity, vibration, and radiation. The physics-of-failure model, however, requires a thorough understanding of the structure and life cycle conditions of the target system and its failure modes and mechanisms [7-10]. Usually, the construction of the accurate physics-of-failure model is extremely difficult, and it might not be possible in some cases.

To resolve these difficulties, a new RUL estimation method is proposed that does not depends on the physics-of-failure models. The proposed method consists of four major steps: 1) identification of environmental factors, 2) extraction of all feasible environmental conditions, 3) computation of a failure rate for each feasible environmental condition, and 4) RUL estimation considering the history of environmental stresses.

In the first step, it is necessary to identify the environmental factors (e.g., temperature, salinity, vibration, seasonal factors, wind direction, and radiation) that affect the RUL of the electronic control board. The environmental factors should be carefully selected in cooperation with field experts. Let us assume that the number of environmental factors is $n$. Then, an $n$-dimensional environmental space can be defined. The second step is to extract all feasible environmental conditions in which the electronic control board may be exposed. A feasible environmental condition is defined as a sub-space in the $n$-dimensional environmental space, as shown in Fig. 2. In the third step, a failure rate for each feasible environmental condition is computed by using a standard procedure for the reliability prediction 'MIL-HDBK-217F' [12]. The last step is to estimate the RUL of the electronic control board by considering the history of environmental conditions (i.e., failure rates) to which the equipment is actually exposed.

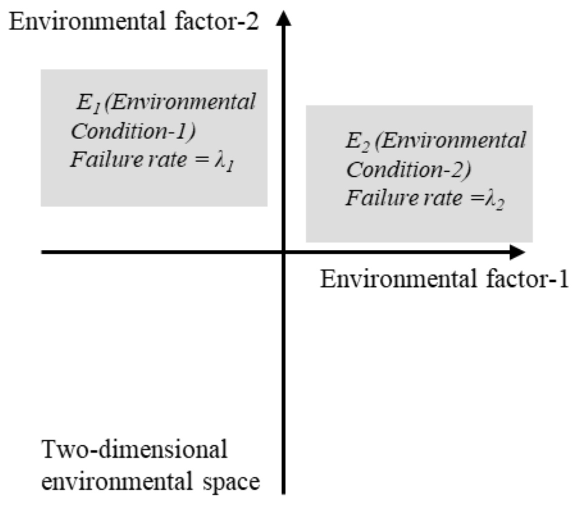


**Fig 2.** Environmental space and environmental conditions

In order to estimate the RUL, the concept of a reliability function was used. A reliability function gives the probability of an item operating for a certain amount of time without failure. Let $T$ denotes the time to failure of a facility, and $f(t)$ is the probability distribution function of $T$. At this time, the reliability of the facility at time $t$ can be defined as the probability that the facility fails after time $t$ ($t > 0$), and the reliability function can be stated as $R(t) = P(T > t) = 1 - \int_0^t f(x)dx$ . In reliability engineering, the exponential distribution is popularly used, and this paper also assumes that $f(t) = \lambda e^{-\lambda t}$, where $\lambda$ is the failure rate. In this case, the expected lifespan becomes the mean time to failure ($MTTF = \int_0^\infty t \cdot f(t)dt = \int_0^\infty R(t)dt = \frac{1}{\lambda}$). Fig. 3 shows a series system which fails if any one of the components fails. The reliability function of a system that contains multiple components can be defined by the combination of the component reliability functions as shown in Fig. 3.

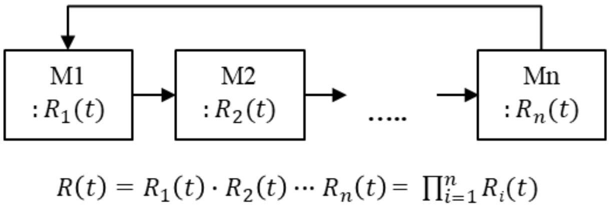


**Fig 3.** Reliability function of a series system consisting of $n$ components

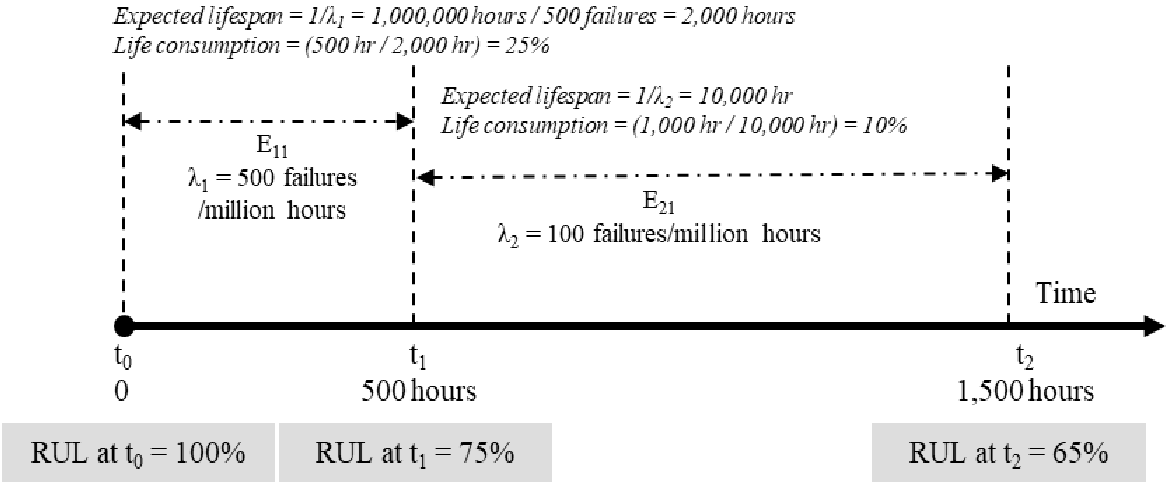


**Fig 4.** Proposed life consumption model considering accumulated damages

Fig. 4 shows an example explaining how the proposed RUL estimation method works. In the beginning at $t_0$, the RUL becomes 100% because there is no life consumption yet. The failure rate ($\lambda_1$) of the first operating period ($t_0 \sim t_1$) is 500 failures per million hours under the given environmental condition ($E_1$). Since the expected lifespan is the inverse of the failure rate, it becomes 2,000 hours $\left(= \frac{1}{\lambda_{11}} = \frac{1{,}000{,}000\ hours}{500\ failures}\right)$. The first operating period is 500 hours, and it is a quarter of the expected lifespan (i.e., 2,000 hours). As a result, the life consumption during the first operating period is 25% (a quarter), and the RUL becomes 75% at $t_1$. In the same way, the life consumption of the second period (i.e., 10% of the expected lifespan) can be calculated, and the RUL becomes 65% at $t_2$.

Once a failure rate table is prepared, it is possible to compute the RUL by considering the history of environmental conditions (or environmental stresses). The environmental history can be obtained by monitoring information from sensors. As explained earlier, the RUL can be updated by subtracting life consumption from a remaining lifespan. The proposed algorithm can be described as follows.

RUL computation algorithm:

// Input: $E_i, 1 \leq i \leq n$, a history of environmental conditions

// Output: $RUL$, the remaining useful life of an electronic control board

Step 1) Initialize:

    $RUL$ = 100;    // 100% of remaining useful life

Step 2) For ($i = 1$ ; $i \leq n$ ; $i++$) {   // For each environmental condition

    Step 2-1) $\lambda$ = the failure rate of ($E_i$);

    Step 2-2) $TD$ = the time duration in ($E_i$);

    Step 2-3) $LE = 1/\lambda$;    // expected lifespan under ($E_i$);

    Step 2-4) $LC = TD/LE$;    // life consumption under ($E_i$);

    Step 2-5) $RUL = RUL - LC$;    // update RUL by deducting life consumption;

    }

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The proposed algorithm updates RUL by deducting the amount of life consumption caused by environmental stresses. The RUL estimation is useful to the maintenance decision making process, which can be tactical (i.e., real time interpretation and feedback) or strategic (i.e., maintenance planning). Although the estimated RUL provides useful information to service providers, it alone does not provide sufficient information to form a decision or to determine corrective action. Service providers need to make maintenance related decisions by comprehending the corresponding measures of the uncertainty associated with the RUL calculation.

## III. RUL ESTIMATION OF THE ELECTRONIC CONTROL BOARD IN A TRAFFIC SIGNAL CONTROLLER

Traffic signals are electronically operated control devices, and the normal function of them includes the control and coordination to ensure that traffic moves as smoothly and safely as possible. Traffic signals also allow an opportunity for pedestrians or vehicles to cross an intersection and to lessen the number of conflicts between vehicles entering intersections from different directions. An autonomous traffic signal controller should be designed to perform well without human guidance under significant uncertainties in the system and environment for extended periods of time. The electronic control board in an autonomous traffic signal controller used as an example in this paper is shown in Fig. 5. It consists of 151 electronic components, such as integrated chips, capacitors, and resistors.

As mentioned earlier, the proposed method consists of four major steps: 1) identification of environmental factors, 2) extraction of all feasible environmental conditions, 3) computation of a failure rate for each feasible environmental condition, and 4) RUL estimation considering the history of environmental stresses. In the first step, it is necessary to consider the operation conditions which are affected by temperature, airborne salinity, seasonal factors, distance from the shore, local landscape, wind direction and velocity etc. After consultation with field experts on traffic signal controllers, two dominant environmental factors were selected: temperature and airborne salinity.

The second step is to extract feasible environmental conditions from the environmental space defined by temperature and airborne salinity. In South Korea, the temperature inside the cabinet can rise to 70 ℃ in the summer and down to -20 ℃ in the winter. It is well known that the operating temperature affects the reliability of electronic components. Another major environmental factor is the airborne salinity which refers to the content of gaseous and suspended salt in the atmosphere. The lifespan of an autonomous control system installed close to the coast is shorter than that of an autonomous control system installed inland. Since it is the salt that is deposited on the metal surface that affects the corrosion, the airborne salinity is often measured in terms of deposition rate in units of $mg/m^2/day$.

151 components

Integrated chip
Capacitor
Resistor
LED
Oscillator
Socket
Connector
RAM
ROM
Dallas
Array
Diode
Battery
…

| Component | Type | Quantity | Reference Designator |
|---|---|---|---|
| IC | 74HC245 SMD | 6 | U13 |
| | HIN232 | 9 | U5~7.9.14.15.18.30.31 |
| | XC9572-PC84-7PQFP | 1 | U12 |
| | 74F245 SMD | 1 | U1~4.10.11 |
| | 74HC14SMD | 2 | U16.28 |
| | 74HC573 SMD | 1 | U26 |
| | 80386EXTC-25 PLCC | 1 | U27 |
| | MAX690 | 1 | U29 |
| | 470 -9P | 1 | RA2 |
| Capacitor | 100μF/35V | 1 | C3 |
| | 1μF/35V | 36 | C6~41 |
| Resistor | 1K 1/4W 5% | 1 | R.19 |
| | 10K 1/4W 5% | 10 | R4~8 14~17,22 |
| | 33K 1/4W 5% | 1 | R12 |
| | 16K 1/4W 5% | 1 | R13 |
| | 470 1/4W 5% | 1 | R20 |

**Fig 5.** Bill of materials of the electronic control board in a traffic signal controller

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The airborne salinity is strongly dependent on many variables such as distance from the shore, local landscape, wind direction and velocity etc. According to the ISO classification of salinity levels, the deposition rate of NaCl of coastal area is larger than 3 $mg/m^2/day$, and that of non-coastal area (i.e., inland) is smaller than 3 $mg/m^2/day$. In general, high salt deposition rate tends to result in high rates of corrosion. By considering the two environmental factors, six feasible environmental conditions are extracted, as shown in Fig. 6.

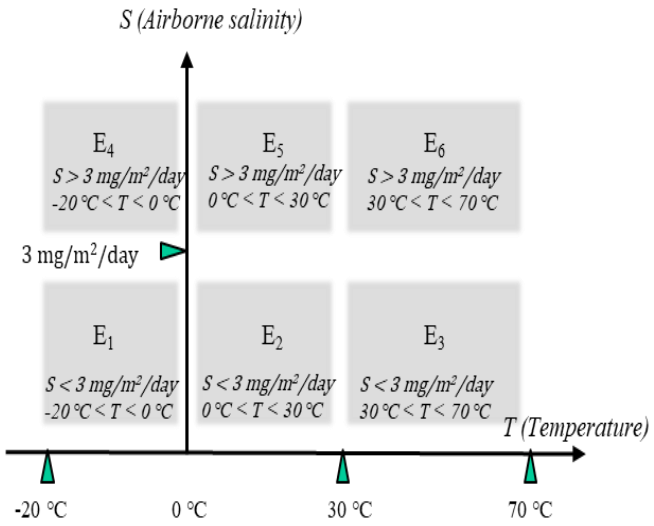


**Fig 6.** Feasible environmental conditions for the electronic control board in a traffic signal controller

The third step is to compute a failure rate for each feasible environmental condition by using the reliability function of the electronic control board. In this paper, the standard procedure for the reliability prediction 'MIL-HDBK-217F' [12] has been made. The electronic control board is a series system consisting of 151 components, and its reliability function can be defined by combining the reliability functions of components, as shown in Fig. 3. A component reliability function can be obtained by computing the failure rate of the component under a given environmental condition. For example, the failure rate of a ' resistor' (temperature: 10 ℃, deposition rate of NaCl < 3 $mg/m^2/day$) is computed by an equation defined in 'MIL-HDBK-217F' [12], $\lambda_P = \lambda_b \pi_T \pi_P \pi_S \pi_Q \pi_E$, where is $\lambda_b$ a base failure rate, $\pi_T$ is a temperature factor, $\pi_P$ is a power factor, $\pi_S$ is a power stress factor, $\pi_Q$ is a quality factory, and $\pi_E$ is an environment factor. For the given environmental condition (i.e., 10 ℃ of temperature and deposition rate of NaCl < 3 $mg/m^2/day$ ), the failure rate of the resistor becomes 0.071319 failure per million hours. In this way, all failure rates of 151 electronic components can be calculated for given environmental conditions. By combining them as a series system, the failure rates of the electronic control board can be obtained as shown in Fig. 7.

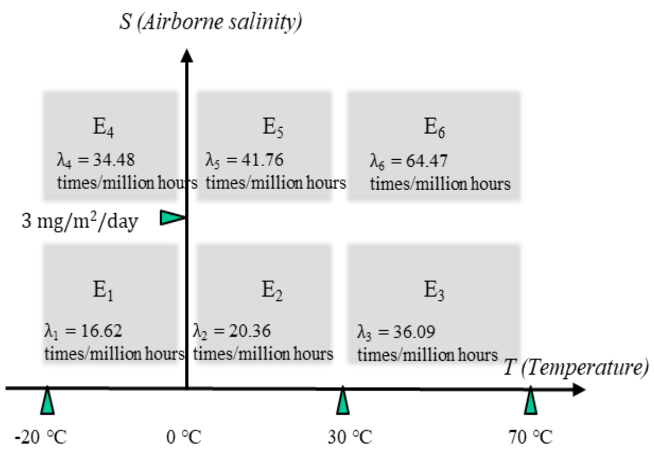


**Fig 7.** Failure rate of all feasible environmental conditions

The fourth step is to estimate the RUL of the electronic control board by considering the history of environmental stresses. For effective demonstration, Chuncheon and Seogwipo cities were selected for different environmental conditions in South Korea. Chuncheon is non-coastal and known for its cold weather in winter, while Seogwipo is costal and relatively warm. For both cities, the temperature recorded data for 2017 were obtained through the Korea Meteorological Administration. Fig. 8 shows the temperature record data. It is known that the inside temperature of a traffic signal controller is about 10 degrees higher than the outside temperature, and the temperature difference is usually caused by the heat of the electronic circuits inside the traffic signal controller.

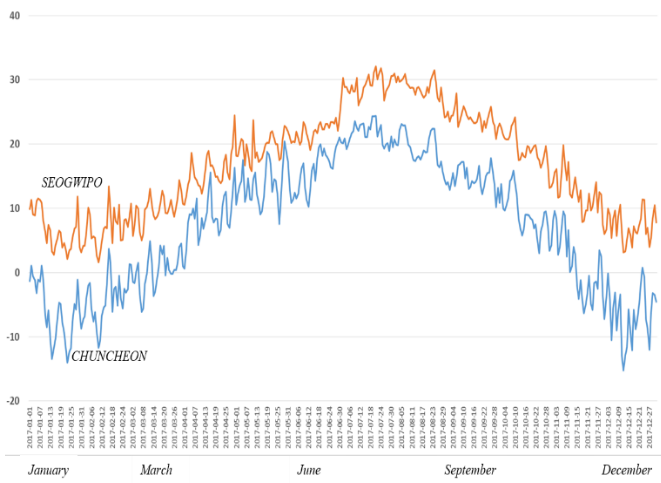


**Fig 8.** Annual temperatures of the two cities: Chuncheon and Seogwipo

The time durations for all environmental conditions are extracted by analyzing the temperature recorded data as shown in Table 1. The amount of life consumption for each environmental condition can be calculated by using the failure rates shown in Fig. 7. At this time, the 'RUL computation algorithm' can be used to estimate the RULs after one year in two different cities as shown in Table 2.

**Table 1.** Time duration in each environmental condition

| | Low T ($t < 0$ ℃) | Medium T (0 ℃$\leq t < 30$ ℃) | High T ($t \geq 30$ ℃) |
|---|---|---|---|
| Chuncheon | 524 hours | 7,099 hours | 1,137 hours |
| Seogwipo | 0 hours | 5,250 hours | 3,510 hours |

**Table 2.** Life consumption in each environmental condition

| | Low T ($t < 0$ ℃) | Medium T (0 ℃$\leq t < 30$ ℃) | High T ($t \geq 30$ ℃) | RUL after 1 year |
|---|---|---|---|---|
| Chuncheon | 0.86 % | 14.45 % | 4.1 % | 80.58 % |
| Seogwipo | 0 % | 21.92 % | 22.63 % | 55.45 % |

In Chuncheon, the RUL of the traffic signal controller is 80.58 % $(= 100 - 0.87 - 14.45 - 4.1)$, but in Seogwipo, the RUL is only 55.45 % $(= 100 - 0 - 21.92 - 22.63)$ as shown in Table 2. This result means that the RUL decreased rapidly because the environmental conditions in Seogwipo is harsh for the traffic signal controller. In fact, it is well known that the lifespan of a traffic signal controller is especially short in warm coastal cities. In conclusion, the RUL estimated by the proposed method agrees well with the existing observations.

## IV. CONCLUSION

In this paper, a new method for estimating the RUL of the electronic control board in an autonomous control system is proposed. The proposed method belongs to the life consumption monitoring approach, but does not rely on the physics-of-failure model that is extremely difficult to construct. The proposed method calculates the RUL using a standard procedure for the reliability prediction instead of using the physics-of-failure model. The proposed method consists of four major steps: 1) identification of environmental factors, 2) extraction of all feasible environmental conditions, 3) computation of a failure rate for each feasible environmental condition, and 4) RUL estimation considering the history of environmental stresses.

The product used as a case study is an electronic control board of a traffic signal controller, and the control board is composed of 151 electronic components such as integrated chips, capacitors, and resistors. The main environmental factors affecting the lifespan of the electronic control board are temperature and airborne salinity. Two cities with different environmental conditions are selected to demonstrate the feasibility of the proposed RUL estimation method. After one year of operation, the RUL in Chuncheon and Seoqwipo is 80.58 % and 55.45 %, respectively. As a result, it was confirmed that the RUL estimated by the proposed method agrees well with the existing observation.

The proposed method updates the RUL by deducting the amount of life consumption caused by environmental stresses. The RUL estimation is useful for maintenance decision making process, which can be tactical or strategic. All PHM approaches are essentially extrapolation of trends based on recent observations to estimate RUL. The estimated RUL provides useful information to service providers, but does not provide enough information to make a decision or make a corrective action. Service providers need to make maintenance related decisions by comprehending the corresponding measures of the uncertainty associated with the RUL calculations.

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