

## Subjective Logic Dynamic Model and its Application Research

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### Abstract

*In Jøsang's subjective logic, the consensus operator will have unreasonable results when the evidence with high conflict; the base rate ( $a$ ) and non-informative prior weight ( $C$ ) could not change dynamically. This paper proposed a dynamic subjective logic model that expand and rich the theory of Jøsang's subjective logic. Through the establishment of a cartesian coordinate system and using line / curve fitting algorithm to outline the dynamic track of the opinion, it can more intuitively observe the change and development tendency of the opinions in different observation periods. At the same time, according to different application environment, the dynamic function of the base rate ( $a$ ) and non-informative prior weight ( $C$ ) were given. The subjective logic was extended to five tuples and the consensus operator was improved. The new consensus operator not only met the commutative and associative but also was consistent with cognitive rules of the people. A strict mathematical proof was given. Finally, through the simulation experiments, the results show that the subjective logic improved more reasonable and effective. It could be better adapted to the changing environment.*

**Keywords:** *subjective logic; dynamic; weight; the line / curve fitting*

### 1. Introduction

With the development of large-scale distributed systems, such as the cloud computing, Ad Hoc network, the security and reliability of the systems are more concerned. Because these systems have open, dynamic and uncertain characteristics, the corresponding model theories put forward higher requirements. At present, the trust relationship is mainly expressed by the trust model. According to theoretical basis, the trust model can be divided into: trust model based on fuzzy logic; trust model based on reputation; trust model based on subjective logic and node behavior; analytic hierarchy process and fuzzy logic combined type [1]. Among them, the trust model based on subjective logic proposed by Jøsang is more suitable for modeling the trust of dynamic uncertainty object. Jøsang learned from the D-S evidence theory, put the uncertainty into the model and proposed the subjective logic theory. Jøsang put the uncertainty into the model for building the trust relationship and achieved good results. However, there are some issues that the base rate ( $a$ ) and non-informative prior weight ( $C$ ) can't dynamic changes in Jøsang's subjective logic and the consensus operator may have unreasonable results in the situation that the evidence with high conflict. If we can

solve these problems, it has a role in promoting the development and perfection of Jøsang's subjective logic theory and rich the trust model.

## 2. Related Work

In recent years, the research on the Jøsang's subjective logic trust model has achieved fruitful results. Subjective logic proposed by Jøsang *et al.*, [2] can express subjective uncertainty, and it has achieved gratifying results [3-8]. Its Beta trust model, which successfully applied in the open community of the trust management, has become one of the classics in trust management field. Ref. [3] uses subjective logic for trust network analysis, however, the discounting operator will lead to trust value decline too fast in trust transfer process. Ref. [4] reviews the current trust and reputation systems. Ref. [5] uses conditional reasoning to extend binomial opinions to multinomial opinions for improving and perfection the subjective logic, but the multinomial fusion operator still does not meet the commutative and associative law and lead to the fusion result is not unique in the fusion of three or more opinions. Ref. [6] points out the rich features of Bias's reputation system, which is applicable to many different problems and environmental. Ref. [7] designs the cumulative fusion operator and the average fusion operator for improving the subjective logic, while the issue mentioned above is still exist. Ref. [8] redefines the mapping from the condition to result by using subjective logic. The subjective logic provides the theoretical foundation of a good trust representation and reasoning for trust management, so the study of subjective logic is gradually valued by researchers. Ref. [9] presented the time related trust and extended subjective logic, but the model can not solve the problem this paper proposed. The ref. [10] proposed anomaly detection framework using subjective logic. Ref. [11] proposed a trust model based on subjective logic and the risk mechanism. Ref. [10, 11] are general applications of subjective logic, because the issues proposed by this paper are still exist, the accuracy of the results got by these model is poor. Some scholars have pointed out that the consensus operator in some cases will produce unreasonable result [12], and the consensus operator was modified. But it does not consider that the three tuples must be satisfying additivity of probability, the modified consensus operator does not meet the nature. H Zhou [13] *et al.*, pointed out that the discounting operator increased uncertainty in the operation the consensus operator problems. It proposes a weight method to improve the consensus operator. But it carries out the discount operation in the calculation of trust value  $b$ , the relative uncertainty increases slightly. In ref. [12, 13], the improved consensus operator does not meet the commutativity law and associativity law when fusion multiple opinions. This limits the practical application.

This paper proposed a dynamic subjective logic model and extended the theory of Jøsang's subjective logic. The main work includes :(1) According to the different application environment, were given the dynamic function of the base rate ( $a$ ) and non-informative prior weight( $C$ ).At the same time, using the line / curve fitting algorithm outline the dynamic track of the opinion, can more intuitively observed in change and development tendency of different observation periods shown. It not only obeys mathematical rules, but also can better reflect the objective reality. (2) The subjective logic is extended to five tuples and the consensus operator is improved. The consensus operator improved to meet the commutativity law and associativity law. It also accords with the cognitive law and gives a strict mathematical proof. (3)Carry out the



From the Table 1 we can see the diagnostic results from doctor  $A_1$  and  $A_2 \sim A_4$ . They are significant differences. The results by consensus operator in subjective logic tend to trust the doctor diagnosed  $A_1$ , but not trust the other 3 doctor's diagnosis. This is not consistent with logical thinking.

## 4. The Expansion of Subjective Logic

### 4.1. The Dynamic of the Base Rate $a$

In the same identification frame  $X$ , the base rate  $a$  will change with the space-time change dynamically. Considering the influence of the previous  $N$  base rates  $a_i$ , ( $i=1, 2, \dots, N$ ) to the  $N+1$  base rate  $a_{i+1}$ , it should be the shorter the distance in the time axle, the greater the impact. Figure 2 is the diagrammatic sketch based on the observation cycles distance.  $a_1$  farthest from the  $N+1$  observation  $a_{i+1}$ , so, the influence is minimal. The influence of the former  $N$  base rates are increasing. In the different frame and environment, it can be designed for different functions according to the actual situation, which is shown in Figure 3:

Line1 can be understood as the early observations on the current base rate  $a_{i+1}$  is less affected, while the larger effects of recent observation, the system that is not high on the real-time requirements may apply. Such as, brand reputation value.

Line2 can be understood as the effects appear linear change, with the time increasing, recent observations on the current base rate influence is bigger, and the general systems can be applied.

Line3 can be understood as the recent observation on the current base rate impact is very big, suitable for use in systems for real-time requirements of very high. Such as, security defense system.

We design a linear function fun1 or nonlinear function fun2, in addition, the former  $N$  observations opinion's consensus value  $\omega_{x_j^k}^N = \omega_{x_j^k}^1 \oplus \omega_{x_j^k}^2 \oplus \dots \oplus \omega_{x_j^k}^N$ , its expectation as  $a_{i+1}$  shown in function fun3.

$$\text{fun1 : } a_{i+1} = \sum_{i=1}^N (b_i + u_i a_i) * i / \sum_{i=1}^N N$$

$$\text{fun2 : } a_{i+1} = \sum_{i=1}^N (b_i + u_i a_i) e^{5[(i-1)T-t]/NT} / N$$

$$\text{fun3 : } a_{i+1} = E_{x_j^k}^N = b_{x_j^k}^N + a_{x_j^k}^N \times u_{x_j^k}^N$$

Observation cycles: 1                      2                      3                      ...                      N                      N+1

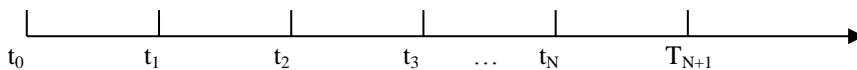
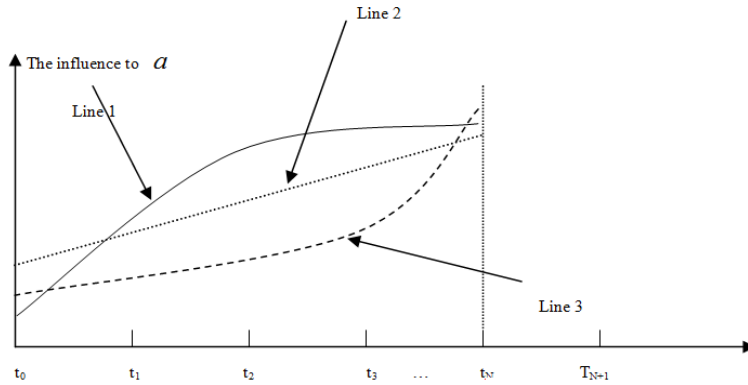


Figure 2. The Diagrammatic Sketch based on the Observation Cycles Distance



**Figure 3. The Influence of the Previous N base Rates  $a_i$  ( $i=1,2,\dots,N$ ) to the N+1 Base Rate  $a_{i+1}$**

#### 4.2. The Dynamic of the Non-informative Prior Weight C

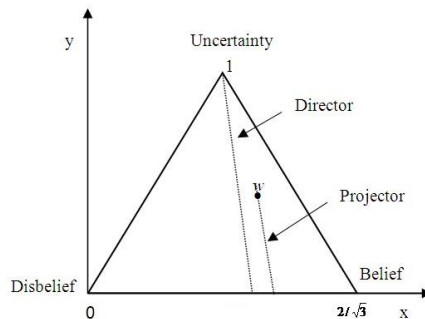
C should be increase with the problem size k (the cardinality in the polynomial opinion), while decreases with the increasing evidence N (observation times) or t (time). Therefore, it could design linear function or nonlinear function according to the actual situation. such as fun4 and fun5. r is the adjustment coefficient in fun4, and its role in the regulation of C decline rate.

$$\text{fun4: } C(N, k) = rk / N \quad (0 < r < 1)$$

$$\text{fun5: } C_{i+1} = ke^{-N}$$

#### 4.3. The Rectangular Coordinate System

According to Jøsang defined triangle graphics, the rectangular coordinate system is shown in figure Figure 4.



**Figure 4. The Rectangular Coordinate System of the Opinion**

We give the function equation of Projector and Director and the coordinate of the opinion  $\omega$  :

$$\text{Projector: } y = 2 / (1 - 2a) [ x - (b + ua) ]$$

Director:  $y = 2 / (1 - 2 a) [ x - a ]$

The coordinate of  $\omega : ( b + u / 2 , u )$

Subjective logic is mainly used to trust quality distribution of the opinion, while the trust varies with time and space environment. Breaking away from the time and discussing trust is of no significance. So, we increase in time dimension on the basis of the rectangular coordinate system and establish the three-dimensional coordinate system through periodic observation of the opinion  $\omega$ , see in Figure 5.

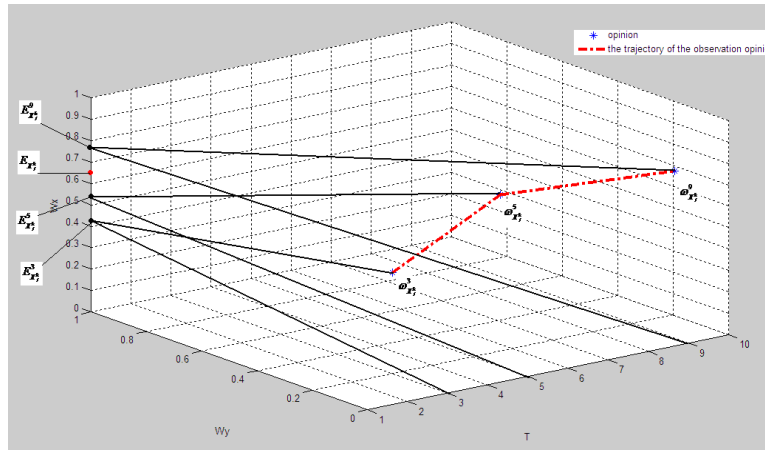


Figure 5. Three-dimensional Coordinate System

#### 4.4. The improving Consensus Operator

Let  $\omega_x^A = \{ b_x^A, d_x^A, u_x^A, a_x^A \}$  and  $\omega_x^B = \{ b_x^B, d_x^B, u_x^B, a_x^B \}$  be opinions respectively held by agents A and B about the same proposition x. Let  $\omega_x^{A,B} = \{ b_x^{A,B}, d_x^{A,B}, u_x^{A,B}, a_x^{A,B} \}$  be opinion such that

$$\begin{aligned}
 1 \quad b_x^{A,B} &= (W_A b_x^A + W_B b_x^B) / (W_A + W_B) & 2 \quad d_x^{A,B} &= (W_A d_x^A + W_B d_x^B) / (W_A + W_B) \\
 3 \quad u_x^{A,B} &= (W_A u_x^A + W_B u_x^B) / (W_A + W_B) & 4 \quad a_x^{A,B} &= (W_A a_x^A + W_B a_x^B) / (W_A + W_B)
 \end{aligned}$$

$W_A$  and  $W_B$  be weights respectively had by agents A and B such that both  $W_A$  and  $W_B \in (0, 1)$ . Then  $\omega_x^{A,B}$  is called the consensus between  $\omega_x^A$  and  $\omega_x^B$ , representing an imaginary agent [A, B]'s opinion about x, as if she represented both A and B. By using the symbol ' $\oplus$ ' to designate this operator, we define  $\omega_x^{A,B} = \omega_x^A \oplus \omega_x^B$ .

The consensus operator in Jøsang's subjective logic is not meeting the associativity law, here, give the multiple opinions fusion algorithm. For meeting the associativity law, we define the calculation method of the "consensus weight". For example, the consensus weight of the opinion  $\omega_x^{A,B}$  is  $W_{A,B} = W_A + W_B$ .

Supposing that the opinion of  $i_{th}$  observer is  $\omega_x^i = \{ b_x^i, d_x^i, u_x^i, a_x^i \}$   $i \in [2, N]$ , N opinions are fusion by the new consensus operator,

$$\begin{aligned}
 1 \quad b_x^N &= \left( \sum_{i=1}^N W_i b_x^i \right) / \left( \sum_{i=1}^N W_i \right) & 2 \quad d_x^N &= \left( \sum_{i=1}^N W_i d_x^i \right) / \left( \sum_{i=1}^N W_i \right)
 \end{aligned}$$

$$3 \quad u_x^N = \left( \sum_{i=1}^N W_i u_x^i \right) / \left( \sum_{i=1}^N W_i \right) = 1 - b_x^N - d_x^N \quad 4 \quad a_x^N = \left( \sum_{i=1}^N W_i a_x^i \right) / \left( \sum_{i=1}^N W_i \right)$$

Discovered by the research on the consensus operator above, when two observers hold the same opinion value, through the calculation of the new consensus operator, the fusion result is same with the opinion value. But by intuition, it should reflect a cumulative effect. In the new consensus of the calculation process, the change is reflected by "consensus weight". In another words, to the same opinion value, the consensus weight reflect the cumulative effect. Therefore, we put the consensus weight into the  $\omega$ , and expressed as 5 tuples:

$$\omega_x = \{ b_x, d_x, u_x, a_x, W_x \}.$$

**Commutativity Law Proving:**

Due to the symmetry of the new consensus operator design, can be proved easily meet the commutativity law, this proved slightly.

**Associativity Law Proving:**

Without loss of generality, to three point of fusion as an example:  $\omega_x^A = \{ b_x^A, d_x^A, u_x^A, a_x^A, W_x^A \}$ ,  $\omega_x^B = \{ b_x^B, d_x^B, u_x^B, a_x^B, W_x^B \}$  and  $\omega_x^C = \{ b_x^C, d_x^C, u_x^C, a_x^C, W_x^C \}$  are the opinion of the agents of A, B, C to the X. Proving that associativity law only needs to prove the following holds, here, take b as an example.

$$\omega_x^N = \omega_x^A \oplus \omega_x^B \oplus \omega_x^C = (\omega_x^A \oplus \omega_x^B) \oplus \omega_x^C = \omega_x^A \oplus (\omega_x^B \oplus \omega_x^C).$$

$$b_x^N = \left( \sum_{i=1}^N W_i b_x^i \right) / \left( \sum_{i=1}^N W_i \right) \text{ and } b_x^{A,B} = (W_A b_x^A + W_B b_x^B) / (W_A + W_B)$$

$$b_x^{A,B} \oplus b_x^C = (W_{A,B} b_x^{A,B} + W_C b_x^C) / (W_{A,B} + W_C)$$

$$= (W_A b_x^A + W_B b_x^B + W_C b_x^C) / (W_A + W_B + W_C) = \left( \sum_{i=1}^N W_i b_x^i \right) / \left( \sum_{i=1}^N W_i \right) = b_x^N$$

$$b_x^A \oplus b_x^{B,C} = (W_A b_x^A + W_{B,C} b_x^{B,C}) / (W_A + W_{B,C})$$

$$= (W_A b_x^A + W_B b_x^B + W_C b_x^C) / (W_A + W_B + W_C) = b_x^{A,B} \oplus b_x^C = b_x^N$$

Q.E.D. The same can be said for a, d, u satisfies the associativity law.

**5. Example Analysis**

Example1: We still take example in [12] as an example. Analysis the results using the new consensus operator in case that the doctors with different weights. The results are shown in Table 2:

**Table 2. The Judgment Value in the Same and Different Weights Situation**

Experiment N	A1'weig ht	A2'weight	A3'weight	A4'weight	The result {b,d,u}
1	0.8	0.8	0.8	0.8	{0.225, 0.7, 0.075}
2	0.9	0.1	0.1	0.1	{0.6, 0.367, 0.033}
3	0.8	0.9	0.6	0.7	{0.24, 0.687, 0.073}

Experiment 1: When the four doctor weights are same, we use new consensus operator to calculate subjective logic value d=0.7. Judging from the results, it expressed that the patient

had meningitis are less likely to have cerebral concussion in A2 ~ A4 point of view and the possibility is larger. It conforms to the intuition of people and accords with the actual situation.

Experiment 2: It is a more extreme example, when Dr. A1's weight is very high (as the authoritative expert clinicians) and A2 ~ A4 doctor weight is very low (as the interns), in this case, the result  $b=0.6$ . The viewpoint expressed by authoritative experts doctor A1 that the patient gets meningitis with high probability. This is conforming to the intuition of people and according with actual situation.

Experiment 3: When the four doctor with difference weight but not big, in general, judging from the results,  $d=0.687$ . On A2 ~ A4 viewpoint, namely in the doctor's weight is not very different circumstances, it conforms to the intuition that the minority is subordinate to the majority.

## 6. Simulation Experiments

The experiment data set is selected from the KDDCUPK99. We select 36000~42000 records from the corrected data as experiment data. Assume that there are 600 records in each observation period and then there are 10 observation periods. Each of the 600 records were given by 6 observers separately, that is to say, each observer is provided 100 records. In order to use the new consensus operator, assume that 6 observers' weights are  $\{0.5, 0.9, 0.7, 0.6, 0.8, 0.8\}$ . The statistical positive event number for calculating the  $\omega$  coordinates, the description see Table 3. The initial  $a = 0.1$ . Using equation fun1 and fun4, in our model,  $a, C$  will change dynamically with observation periods, while  $a=0.5, C=2$  in Jøsang's model. This paper has also carried on  $a, C$  static constant experiments, i.e.  $a=0.5, C=2$ . And compare with  $a, C$  in the dynamic change of situation.

**Table 3. 6000 Records for Positive Event Statistics**

cycle observer	1	2	3	4	5	6	7	8	9	10
B1	91	86	91	78	93	88	88	82	0	60
B2	84	86	86	66	88	92	90	90	0	67
B3	92	97	88	88	88	93	87	76	54	48
B4	88	88	75	90	91	82	95	60	73	61
B5	89	91	72	91	90	88	86	3	59	35
B6	94	87	71	92	96	90	86	0	62	0

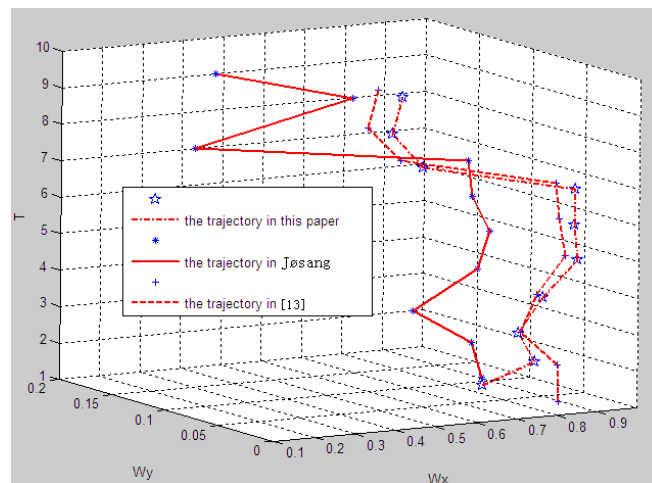
**Table 4. The Coordinates of  $\omega$  in Three Kinds of Model**

Observation cycle number	a, C dynamic changes value and the coordinates of $\omega$ in our model				a=0.5,C=2 the coordinates of $\omega$ in our model		the coordinates of $\omega$ in Jøsang's model		the coordinates of $\omega$ in [13]'s model	
	a	C	B+U/2	U	B+U/2	U	B+U/2	U	B+U/2	U
1	0.5	10	0.877	0.127	0.887	0.020	0.907	0.020	0.893	0.033
2	0.82	5	0.883	0.066	0.874	0.020	0.879	0.020	0.891	0.033
3	0.866	3.3	0.797	0.045	0.794	0.020	0.734	0.020	0.799	0.033



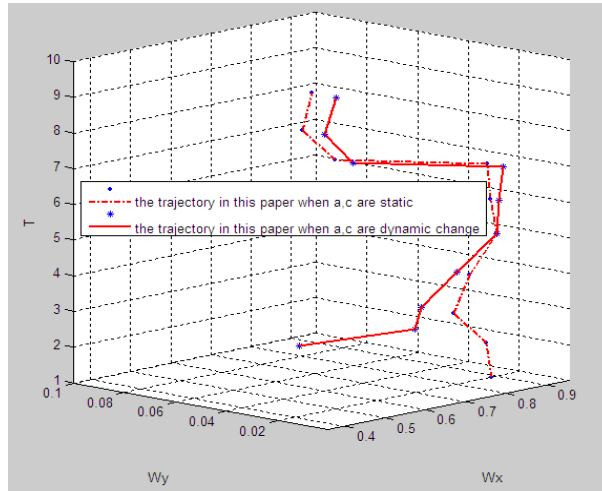
4	0.826	2.5	0.835	0.034	0.832	0.020	0.892	0.020	0.837	0.033
5	0.838	2	0.905	0.027	0.901	0.020	0.922	0.020	0.907	0.033
6	0.861	1.67	0.889	0.023	0.884	0.020	0.879	0.020	0.891	0.033
7	0.869	1.4	0.882	0.019	0.877	0.020	0.866	0.020	0.884	0.033
8	0.873	1.25	0.499	0.017	0.497	0.020	0.190	0.020	0.497	0.033
9	0.791	1.1	0.418	0.015	0.417	0.020	0.581	0.020	0.415	0.033
10	0.715	1	0.441	0.014	0.440	0.020	0.239	0.020	0.439	0.033

In order to observe more convenient, in the three-dimensional coordinates,  $W_x$  axis represents the  $\omega$  of the horizontal coordinates  $b+u/2$ ,  $W_y$  axis represents longitudinal coordinate  $u$ ,  $T$  the time axis represents observation cycle; After curve fitting, the 10 observation cycles trajectory of our model and Jøsang and paper [13] are shown in Fig.6. Through the Fig.6, it can be directly observed that the network state is stable in the former 7 times observation period and the value of  $b$  changes little. The trajectory and the development trend in the three models are consistent, while in eighth observation, the  $b$  values decreased dramatically, it indicates that the network state decreased sharply and was likely to come under attack. The reaction of the eighth observations cycle for the 600 records is consistent. However, when the network state changes, because it does not take into account the effect of the previous observation in Jøsang's image, the expectation value of the opinion has a very great change. The  $b$  value is too sensitive, quickly from 0.8664 down to 0.1899, which is inconsistent with the facts. While the  $a$  and  $C$  will change dynamically in our model, it can reflect the change well and not too sensitive; it can be more accurately reflect the actual situation of the network, especially in the situation that the network has an obvious change, for example, the third cycles and eighth cycles, the image in Jøsang and our model is quite different. As our model and ref. [13] has considered the effect of weight in consensus operation of the opinion, as shown in the figure is basically the same, but on the computational complexity, our model than the scheme ref. [13] proposed is much smaller. Our model meet the consensus operator the associativity law, to ensure that data reordering does not affect the final result in many times of observation, while the other two did not meet this, namely the consensus results is not unique. The consensus result depends on the order of consensus operation, which is obviously unreasonable.



**Figure 6. The 10 Observation Cycles Trajectory of  $\omega$  in Three Models**

Figure 7 is shown that the comparison of  $a$ ,  $C$  static and dynamic changes in the trajectory of ten observation cycle, the changes of  $a$ ,  $C$  values are shown in Table 4, found that, when  $a$ ,  $C$  are static, the uncertainty of  $\omega$  is not change, namely the longitudinal coordinate ( $u$ ) remains unchanged. Due to the actual situation, with the increase in the number of observations, the uncertainty should be gradually reduced. Therefore, the dynamic changes of  $a$ ,  $C$  are more able to adapt to changing circumstances.



**Figure 7. The Comparison of  $a$ ,  $C$  Static and Dynamic Changes in the Trajectory of  $\omega$  in our Model**

## 7. Conclusion

This paper proposed a dynamic subjective logic model that expand and rich the theory of Jøsang's subjective logic. Through the establishment of a cartesian coordinate system and using line / curve fitting algorithm to outline the dynamic track of the opinion, it can more intuitively observe the change and development tendency of the opinions in different observation periods. At the same time, according to different application environment, the dynamic function of the base rate ( $a$ ) and non-informative prior weight ( $C$ ) were given. The subjective logic was extended to five tuples and the consensus operator was improved. The new consensus operator not only met the commutative and associative but also was consistent with cognitive rules of the people. A strict mathematical proof was given. Finally, through the simulation experiments, the results show that the subjective logic improved more reasonable and effective, can better adapt to the changing environment. We are going to work further on discuss how to set the weight of scientific and reasonable.

## Acknowledgements

This work was supported in part by The National Natural Science Foundation of China (61170254, 60873203), the University of Hebei province science and technology research program (ZH2012029) and the natural science foundation of Hebei province (F2014201117).

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