Development and Evaluation of Artificial Intelligence Techniques for Tactical Decision Support Systems

Kevin J. Lehnert       Michael Sullivan
Artificial Intelligence Applications Branch
Texas Instruments, Inc
PO Box 556474, MS 238
Dallas, Texas 75265

Abstract

To facilitate research into multi-agent planning issues, we have developed the Command and Control Testbed Using Simulation (CACTUS) and the Situation-based Autonomous Reasoner in a GBB Environment (SARGE). CACTUS is a simulation of combat operations for platoon-sized units in battalion-level engagements. We model in detail those battlefield elements that impact the planning process of the formation commander.

The testbed originally required the user to input specific movement and firing instructions for each simulated unit. Units with SARGE commanders take goal-level instructions and SARGE then reasons about plans to achieve those goals and generates the necessary simulation-level instructions to act on the plan. The SARGE system provides the foundation for developing automated planners for multiple unit formations by abstracting the operation of subordinate units. We are using an incremental approach to address command and control issues at progressively higher levels of the chain of command. Our goal is to develop, refine, and evaluate artificial intelligence techniques to capture and integrate human expertise with machine planning expertise. Our ultimate goal is to collect applicable techniques into a system for rapid prototyping of tactical decision aids. SARGE and CACTUS are vital tools in this process.

Introduction

Battlefield planning is a complex, knowledge intensive task beyond the reach of conventional automation techniques. However, the experience and intuition required limit the number of human experts available. These valuable staff resources provide a needed effectiveness multiplier for field forces and the demand on them in any future conflict will be tremendous. Any automated staff assistant must address aspects of the battlefield planning problem such as scarce resource allocation, reasoning under uncertainty, plan and goal recognition, and communication costs. Our goal is to develop tactical decision aids for some facets of the command process. Such aids would complement the cognitive abilities of the staff for processing and planning \[2,15\] by automating the largely mechanical aspects of staff work.

Our approach is to develop, refine, and evaluate artificial intelligence techniques for capturing and integrating human expertise with machine capabilities. Our evaluation methodology requires a testbed in which the prototype decision aids can operate. We constructed the Command and Control Testbed Using Simulation (CACTUS) to provide a realistically complex model of the problems encountered in battlefield planning. Since the goal of our research is not a body of domain knowledge but a set of techniques applicable to the domain, the absolute fidelity of our models to military reality is less vital. We have represented in CACTUS many domain issues important for evaluating AI planning technologies.

Commanders in the military function within a hierarchical chain of command. Each higher level of the hierarchy controls formations of greater complexity. However, the subordinate formations are themselves capable of planning tasks for their agents to achieve an assigned goal. We needed to raise the level of abstraction of the user’s input from detailed instructions for individual units to abstract goals for the highest levels of the hierarchy. We also needed to have control over all aspects of the simulated force behavior that affect agent responsiveness to commands in order to evaluate the sensitivity of planning approaches to such factors. Our plan is to build automated agent controllers for formations in the simulation, beginning with the single platoon unit. The Situation-based Automated Reasoner in a GBB Environment (SARGE) is the first result of this process. SARGE allows the company commanders to specify mission goals instead of simulation actions for subordinate units. By raising the level of abstraction in the simulation interface and using symbolic descriptions of agent low level behavior, we are focusing on developing planning tools. We are using SARGE to complete the feedback loop between the first level formation commander and the simulation.

In this paper, we begin by describing the CACTUS simulation system. Then we discuss the structure, implementation, and operation of the SARGE commander. Next we illustrate the utility of SARGE in the development of multi-agent commanders. Finally, we describe the current state of our work and future directions.

CACTUS

The Command and Control Testbed Using Simulation (CACTUS) [8] is an object-oriented land combat simulation between Blue and Red forces. CACTUS is a testbed for evaluating battlefield command and control reasoning technologies. The simulation provides a detailed terrain representation including forests, roads, streams, and elevation topology. CACTUS models the military command hierarchy from regiments to Platoons, where each platoon is represented as a single, indivisible unit in the simulation. The simulation manager models command, communications, combat, movement, and viability between units. Multiple predefined engagements are available,
and the user may create new engagements to thoroughly test
different features of experimental planners. CACTUS has ex-
tensive user interfaces for display and simulation control.

Command and Control Models

Command and control within the traditional military hi-
erarchy is a multi-agent planning problem. At any level of
the structure, a number of independent agents work together to
achieve the goals of their superior formation. The agents are
distributed across geographical areas and the communication
between them is imperfect and costly. As the overall situation develops, each
agent has a degree of autonomy in choosing its instantaneous
response. However, the group of agents must coordinate their
actions to achieve a common goal. This requires models of
expected agent behavior, selective communication, and inter-
pretation of plans and goals from the superior formation.

The CACTUS testbed simulates the features of the bat-
tein domain that have the greatest impact on command and
control as a multi-agent planning problem. Therefore, planning
approaches that prove useful in CACTUS agents should have
valid applications in the real battlefield domain. The multi-
agent planning issues correspond to command and control fea-
tures modelled in CACTUS, including:

- **Agent Organization**
  
  The organization of the force structure from the for-
  mational level, the unit (a platoon of about 3-5 vehi-
cles or 20-30 men), to company (team), battalion (task
force), and finally the regiment or brigade, is explicitly
represented.

- **Resource Configuration and Allocation**
  
  At each formation level, commanders can reorganize
the lower level agents by cross attaching them to other
formations. This permits task-specific adjustment of for-
formations for more efficient utilization of available units’
strengths and regrouping of disrupted forces during com-
b.

- **Imperfect Control**
  
  The limited ability of headquarters to assess data
and plan is represented by the availability of limited com-
mand resources. Resources are spent to activate a forma-
tion’s agents to perform tasks. The allocation and con-
servation of command resources are an important part of
the command and control process.

  The formation commander agents are represented by
headquarters units in the simulation. These units are
subject to disruption and destruction by hostile action.
The planning capabilities of disrupted headquarters are
impaired. Also, the cumulative effects of losses and com-
batt can result in formations becoming unresponsive to
orders. These are unique aspects of battlefield planning
as compared with other planning domains.

- **Imperfect Information**
  
  The physical process of communication is modelled.

CACTUS imposes constraints on information flow due to
bandwidth and hostile interference. Since the communica-
tion process is implemented within the simulation sys-
tem, message activity is limited by the flow of simulated
time. These limitations also force the agents to make
judgments concerning the value of the information sent
versus the cost of sending it. By modelling other agents’
probable knowledge of the world, a unit will make better
decisions about communication.

Units receive reports from the simulation system de-
scribing activities viewed by the unit’s simulation entity.
Probabilistic visibility models and dynamic line of sight
calculations are combined to determine what information
the simulation reports to the units.

- **Variety of Agent Capabilities**
  
  Models of 40 different unit types, each with a variety
of weapon systems, movement characteristics, and defen-
sive ratings, are available. The characteristics of each
unit type and weapon system are unique and are used
by the simulation system when resolving combat and ex-
cuting movement. Multiple unit types can be present
within a single formation.

Agent-World Interaction – The simulated world includes
a detailed three dimensional model of the terrain over which the
engagement takes place. The terrain is represented at the lowest
level as hexagonal cells, or hexes. The use of discrete terrain
elements makes spatial calculations for movement, line of sight,
and combat faster. Hexes were selected because of the greater
uniformity in inter-hex relationships than for a grid/square sys-
tem. The real space represented by a hex is adjustable; the
discrete representation can approach a continuous representa-
tion. The computational cost of terrain operations increases
with the number of discrete terrain elements.

Terrain impacts the two primary unit functions: move-
ment and combat. Difficult terrain may impede movement.
The definition of “difficult” depends upon the mobility class
of the unit. An open farm field would not impede the move-
ment of a fully-tracked vehicle, but it could pose a major ob-
stacle for a road-wheeled vehicle. Other unit-specific consid-
erations when calculating movement rates are the deployment
mode (march/column or combat/deployed) and the maximum
vehicle speed. Road networks are also modelled in the terrain
characterization for movement.

Terrain affects combat primarily through a unit’s ability
to avoid detection and to present a more difficult target once
detected. The simulation performs extensive line of sight cal-
culations, taking into account all terrain considerations (eleva-
tion, cover, obstacles, smoke). It is through these limitations
on intelligere available that realistically uncertain situations
are created for the command and control planners. Units can
use surrounding terrain for concealment and securing dug-in
fire positions. Fire combat reflects the lower probability of suc-
}

134
Agent-Agent Interaction – In addition to interacting with the simulated world, agents, through their simulated physical entities, interact with each other. Agents can communicate with each other. A detailed model of communication, through both visual and electronic means, is included in CACTUS. Line of sight has already been discussed. Features of visual contact simulated in CACTUS include concealing terrain, chemical and incendiary smoke, and thermal sights. Electronic communication devices are individually simulated and a model of signal transmission determines the interactions between the messages and the devices.

A second mode of inter-agent interaction is combat. CACTUS has detailed mechanisms for resolving unit combat. Individual weapon systems are characterized by effectiveness versus various target classes. Ammunition load and rate of fire constraints limit fire. Range effects on accuracy and effectiveness are modeled. Unit types are rated for intrinsic defensive capabilities. Combat losses incrementally reduce the strength of units. Losses reflect destruction and disabling of unit components. Combat is resolved as it occurs, with both sides able to initiate fire with eligible units.

User Interfaces

The functions provided to the agent for manipulation of forces within the simulation operate at the unit level. Actions include movement of a unit from one terrain element to another and unit-to-unit fire combat. The agent object is the module through which the simulator interacts with the set of planners for the Red or Blue force. The existence of this module facilitates the distribution of the simulation and agents over multiple processors. The agent object channels the messages issued by the simulation to the unit planner to which the message was directed. The messages are processed within CACTUS through the simulated communication network. They arrive at the agent object and are routed to the planning module.

The primary user interface to CACTUS is interaction through a sequence of menus. Figure 1 shows a typical user display and interface menu. This interface system is also the basis for partially automated agents. In these, the user invokes knowledge-based subsystems that, for example, execute movement for a specified unit or group of units in accordance with user directives. Any number of such subsystems can be integrated into the agent system. Systems that process data and make suggestions are also accommodated by simple modification of the menu-based agent. As more of the functions are automated, user intervention can be reduced to inspection of choices made by subsystems and control of the flow of the simulation.

The planners do not have direct access to the mechanics of the simulation system; they must develop and reason about internal models of the simulated world. The report mechanism, by which observed information is sent to the units, is controlled by the simulation and is the volunteer side of information retrieval. Reports inform units of enemy unit sightings, friendly unit status, and combat results. CACTUS provides interface functions for demand-driven retrieval of less commonly used information. The planner can retrieve information from

![Figure 1: CACTUS User Interface](image-url)
commonly used information. The planner can retrieve information from the simulation that its physical entity would know, but having the simulator volunteer all possibly relevant facts to the agents would be unwieldy.

SARGE

The Situation-based Autonomous Reasoner in a GBB Environment (SARGE) was built to direct the actions of individual units in CACTUS. It interfaces directly to the simulator, effectively replacing the user menu commands previously described. SARGE knowledge-based agents make the testbed accessible to multi-agent commanders that reason at high levels of abstraction by eliminating the requirement that the command planners know the detailed mechanics of the simulation.

Interfaces to CACTUS

To fully automate the interface between SARGE and CACTUS, SARGE must:

- accept the reports CACTUS issues when units sense events, and
- submit actions according to the CACTUS syntax.

SARGE uses the time-coordinating messages issued by CACTUS to all simulation agents to generate legal simulation actions. Information relating simulation phases to legal unit action sets is one of the few CACTUS-specific aspects of SARGE. Otherwise, the reasoning in SARGE is at the level of battlefield domain knowledge. Once the interface functions were implemented, we began to develop the internal structure of SARGE to close the feedback loop.

Blackboard Structure

The architecture we selected for implementing SARGE was the blackboard, or society of experts, model [5,7,10] as implemented in the GBB toolset [6]. This approach is significantly different from a more conventional rule-based expert system. The blackboard consists of data structures with domain attributes. The structures are organized on separate blackboards according to the level of abstraction from the raw domain knowledge they represent. Figure 2 shows the organization of some SARGE data structures on the blackboards. Domain expert processors (called knowledge sources) operate on this data to infer new and more abstract data. This abstracted data is then placed in data structures at higher levels of the blackboard. Each knowledge source performs only a single type of inference or refinement. This fine granularity of expert knowledge supports our approach of building many small tactical decision aids to integrate into a battle management system. The blackboard data structures provide processing waypoints connecting the prototype decision aids.

Another significant benefit of the blackboard approach is that the internal structure of the individual knowledge sources is almost completely unconstrained. In SARGE, we have knowledge sources implemented using Lisp flavors [16], the WORLDS Prolog system [19], and an entire GBB subsystem developed separately. Since the blackboard supports such a diverse software environment, we can evaluate tools as well as techniques and use the best technology and implementation for each task.

Having the domain knowledge explicitly available in small distinct pieces allows us to examine the sensitivity of overall unit behavior to variations in specific modules. For instance, by increasing the length of time over which an enemy unit is tracked, the goal recognition module may make more accurate predictions about the enemy unit destination. However, if the ability of the unit to achieve its goals does not improve in future simulation runs, failure to use this better prediction may be indicated or the capability may not be relevant. Assessing the effect of knowledge source performance on unit goal achievement will allow us to focus on those processes that will have the greatest impact as possible tactical decision aids.

<table>
<thead>
<tr>
<th>SPIRAl BOARD</th>
<th>DATA BOARD</th>
<th>GOAL BOARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRATEGIC</td>
<td>DATA STRATEGIC</td>
<td>AGENDA</td>
</tr>
<tr>
<td>TACTICAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPERATIONAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOCATION</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COMMUNICATION</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 2: SARGE Blackboard Data Structure](image-url)
Example of SARGE Reasoning in CACTUS

SARGE controls its own movement and its firing of weapons. It plans its moves and fires to fulfill goals given to it by its formation commander. The goals are expressed in fairly abstract terms. A typical goal given to SARGE consists of a type of operation (such as attack, defend, or move), a type of objective (such as geographic or informational), an operational area, a constraint on the combat risk SARGE should accept or seek, a constraint on the urgency of beginning the operation, and a constraint on how quickly the objective must be reached [1]. The constraints regulate the discretion SARGE has in planning actions to meet its assigned goal. For example, if SARGE is given a goal with a low acceptable risk level, SARGE will try to avoid combat with enemy units in the course of achieving its goal. If given the same goal with a high acceptable risk level, SARGE will actively seek to combat any enemy units it encounters while pursuing its goal. Some of the actions SARGE takes to achieve a goal are planning a path to reach the operational area and setting its combat readiness features to either move quickly or fire weapons.

SARGE maintains the representation of its current goal to monitor the status of that goal. It is often necessary for SARGE to replan its actions to react to new information or developments. The following example shows how SARGE does this. In the example, figure 3 shows four groups of Blue formations (labelled bHQA, bA1, bA2, and bA3 respectively) and three groups of Red formations (labelled rA1, rHQA, and rA2 respectively (Units rA2 and rHQA actually represent two simulation units, which is why they have two markers). We will discuss the planning done by SARGE for Formation bA3.

SARGE for Formation bA3 has been given a goal to defend the northern half of the terrain in figure 3. The goal's constraints state that the operation requires combat, needs to be achieved quickly, and is of moderate to high urgency. SARGE examines the enemy unit descriptions of rA1, rA2, and rHQA on its Tactical Data blackboard and decides to reinforce the attack of the other Blue formations on rA1, rA2, and rHQA. SARGE, through its path planning expert knowledge sources, plans a path to get in position to attack (figure 4).

As SARGE moves along its planned path, it spots two new Red formations (labelled rB1), as shown in figure 5. This information comes from sensor reports from CACTUS, and arrives at the bottom level of SARGE's data blackboard. SARGE must reassess the situation in light of the new report, and its data fusion and enemy plan recognition knowledge sources construct a new situation assessment structure on the upper level of the blackboard. From the situation assessment SARGE must decide whether to continue executing the current plan or generate a different set of actions. Knowledge sources on the data blackboard estimate the threat posed by rB1. Recognizing that none of the other Blue formations have spotted rB1, and that rB1 represents a clear danger to the success of the mission, SARGE

Figure 3: SARGE Example: Initial Situation

Figure 4: SARGE Example: Initial Plan

Figure 5: SARGE Example: Situation Update
now adjusts its plan in order to defend the southern half of the operational area. The new plan is placed on the upper level of the goal blackboard, and plan refinement knowledge sources convert the plan to individual CACTUS actions. These actions are placed on the bottom level of the goal blackboard.

To implement the new plan, SARGE reinvokes the path planning knowledge sources to plan a new path (figure 6). While SARGE moved along the newly planned path, rB1 has moved closer as well. Since SARGE’s goal allows a high acceptable risk in combat, SARGE makes the decision to attack if the chances of success are high enough. The weapons selection knowledge sources estimate the probabilities of success for various types of attacks. The target selection knowledge sources use these estimates to decide which, if any, enemy formations to attack. In the example, SARGE decided to direct its fire exclusively toward one of the units in rB1. The resulting attack destroyed this unit, as is shown in figure 7.

**Figure 6: SARGE Example: New Plan**

**Figure 7: SARGE Example: Engages Red Threat**

---

**Formation Commanders**

To develop useful tactical decision aids, we have to address one of the most difficult problems in command and control, distributed resource coordination and allocation [4,17]. Where SARGE allows us to examine many planning and assessment problems for a single agent world, the construction of a commander for a set of SARGE agents gives us the opportunity to examine these problems in a distributed world. Solving problems such as balancing communication costs against coordination needs, structuring a set of goals to achieve a single objective, and allocating tasks to remote agents of differing characteristics are areas where tactical decision aids will have their greatest impact [22].

**Levels of Abstraction**

The organization of agents in the domain of military command and control is hierarchical. This structure has been constructed empirically over centuries of military thinking. The primary variable over those years has been the number of controlled agents per commander, or the branching factor. The hierarchical structure must control a given number of assets at the leaf nodes. The depth versus the breadth of the command tree has a great impact on the characteristics of the force. The more agents controlled by a commander (greater breadth), the more complex the planning process for that commander. More plans must be coordinated within a single operational concept. A deeper command structure means fewer agents per commander and greater responsiveness of the commander to variations in the predicted course of events. The costs are less detailed knowledge about the behavior of specific agents (due to the intervening levels of command) and fewer independent agents available to execute the tasks in the formation plan.

SARGE allows the formation commanders to define objectives for subordinate agents at several levels of detail, from explicit movement and firing instructions to mission level goals and operational policies. Planning can proceed incrementally down the chain of command, with abstract directives from above gradually refined into specific instructions at the lowest simulated formation levels. The level of detail of the orders issued at any level depends on the current situation. Therefore, SARGE and the formation commanders must support a flexible goal input vocabulary. In addition, formation commanders must generate orders of varying detail. The integration of SARGE with the CACTUS system enables us to investigate more general issues of multi-agent planning than would be possible if the formation planner had to generate CACTUS action level instructions for each controlled unit.

**Generic Command Model**

The SARGE structure described earlier is a special instance of the generic command model we have developed from our study of command and control literature [3,9,20] and our previous research. The command and control model we use for a military formation commander is a version of the Sense-Interpret-Plan-Act cycle [15]. This cycle is itself an elabora-
tion of the basic stimulus-response paradigm; interpretation and planning are cognitive functions connecting the feedback and feed-forward processes. These two steps serve primarily to focus and guide the responses of the entity over time by creating a projected course of action (Plan) and a world model integrating sensed information and allowing projection of possible futures (Interpretation). We will use this general model as the basis for the multi-agent formation commander currently being developed.

The level of detail of the goal assigned to an agent can vary according to the degree of control policy [14]: in effect. The formation commander must accept and generate goals of appropriate levels of detail for the current situation. A goal with a low level of detail might be "Prevent enemy occupation of Area J." The method of achieving this goal is left to the agent. It could attack known enemy units near Area J; it could establish a defense along the perimeter of Area J; or it could set an ambush in advance of Area J to catch attacking enemy units off guard. With a tighter control policy, one of these more detailed plans could have been explicitly stated by the commander as the mission for the agent, thus restricting the freedom of action of that agent's planner. The commander determines the relative need for coordinated action (more detail) versus quick response (less detail) before selecting the level of detail of the goals generated.

Our thesis is that the generic command model is suitable for all command nodes in the hierarchy. The greatest difference between command levels is the scale of the objects being modeled and manipulated. For example, the sensory input about observed enemy units will generally describe enemy formations of the same size as the sensing commander. The interpretation processes of the commander then use these inputs from multiple subordinate agents to hypothesize the existence and composition of enemy formations of the next formation level larger than the input formations.

The generic command model addresses the assessment and planning issues faced at all levels of command in a hierarchical organization. By attempting to find the similarities between levels, our research into the development of tactical decision aids will impact a greater number of commanders because of the portability of such aids between command levels.

**Current Status**

Both CACTUS and SARGE are currently implemented in the Texas Instruments Explorer™ Lisp Machine environment in Common Lisp with the Flavors system. Our future efforts will focus on specific improvements to CACTUS, SARGE, and the Formation Planners.

**CACTUS Work**

The most important modification we are making to CACTUS is converting it to a time-stamped, discrete event simulation. Currently, the simulation proceeds through an predetermined sequence of phases during each of which only certain actions are allowed and in which only one force may participate. The new CACTUS will present the planners with a more realistic flow of simulated time and greater interaction between simulation units. The early SARGE work required the simpler phasing to limit the number of decisions SARGE had to make. SARGE is now ready to consider more complicated decisions such as those presented by the new simulation structure.

The communication model in the current version of CACTUS does not represent many issues that we feel are important in evaluating tactical decision aid technologies. Messages are explicitly transmitted and received by individual device models, but without attempting to characterize differences due to device parameters. Also, the environmental effects on radio communication are missing. Our goal is to incorporate these factors into the model so that we can evaluate the sensitivity of planning strategies to interruption and degradation of inter-unit communications.

Another area of CACTUS on which we are focusing is the physical distribution of the software modules over multiple processors. As the complexity of the planners increases and more toolsets are used to construct knowledge sources, the demands of hosting both the simulation software and the planners will overwhelm a single processor. We have experience in distributing simulation software and agent modules [18] and we are applying this knowledge to distributing CACTUS. By using Common Lisp, we can use host systems other than the Explorer; for example, CACTUS has been ported to the MicroExplorer system.

**SARGE Work**

One of the current areas of investigation in SARGE is arbitrating between knowledge sources representing conflicting perspectives about a proposed assessment or plan. The partitioning of domain knowledge into many highly-focused modules (KS's) makes the integration of new knowledge very simple, since it needn't be integrated with existing knowledge sources explicitly. The burden of integration rests with the arbitration mechanics. For those cases where all possible solutions can be generated from information available, a simple comparison scheme is adequate. However, for more complex structures such as route plans, the set of possible solutions is too large to be enumerated. In this case, knowledge sources must make constructive suggestions for improvements to an existing solution instead of simply evaluating the current solution.

We are also working to enable SARGE to project possible enemy unit objectives from past observed actions, to anticipate the presence of other enemy from order of battle information, and to model the knowledge state of other friendly units in order to make better decisions about when and what information to transmit.

**Formation Planner Work**

The main thrust in our current work on the multi-agent formation planner is the integration of case-based reasoning for...
strategy selection. Case-based reasoning is an artificial intelligence technique where comparison of the current situation with past experiences is used to select a response to the situation [11,12]. In the formation planner, the case-based reasoning knowledge source will attempt to match the current situation description with a library of past engagements and select a strategy used successfully in the past. The commander can fall back on "first principles" planning methods when no similar experiences exist. In this case, a new memory including the strategy selected and the result of using the strategy is added to the case base for future recall.

Other facets of the multi-agent problem we are addressing are the allocation of tasks and scarce resources to the agents available to execute the formation plan, monitoring of the execution of the plan, and dynamic replanning when expectations fail. We will be integrating our solutions to these issues into the existing blackboard structures.

Summary

We are currently extending the SARGE structure to the problem of multi-unit command. The need to allocate tasks to many subordinate units in order to achieve the overall objective will present us with new challenges, but we are convinced that the inherent flexibility of the blackboard approach and our decision framework will allow us to apply many of the lessons learned in developing SARGE to this new problem. The fine granularity of the problem solving components will ease the transition of subsystems from parts of an autonomous control system to tactical decision aids for commanders and staff, while the overall blackboard framework will allow the smooth integration of arbitrary sets of both human-based and machine-based subsystems into a single decisionmaking system.

References