International Journal of Unique and New Updates (IJUNU)
Volume 7, Issue 1, January- June, 2025, Available online at: www.ijunu.com

Navigating the Landscape of Kubernetes Security Threats and Challenges

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ABSTRACT

Kubernetes has become the new standard for container orchestration, where it allows such organizations to manage applications. Alas, these features make it quite difficult to secure the containerized workloads, primarily this is due to its distributed nature and complexity that inherently poses multiple security threats. This paper aims to provide an overview on how Kubernetes works more specifically about the API Server, the Scheduler and the Controller Manager but also to discuss about the integrated security mechanisms such as the RBAC or Network Policies. Some of the threat categories discussed in detail are misconfiguration threats, container threats, network-oriented attacks, attacks on API servers, and supply chain attacks. This research elaborates on how these vulnerabilities appear, how they affect Kubernetes environments, and ways of preventing such, such as implementing strong configurations, encryption, constant monitoring, as well as dependency control. Through such aspects, this work highlights the need for incorporating active multidimensional approach to security to counter new threats. The insights presented herein are intended to assist organizations using Kubernetes to derive practical knowledge of methods to protect containerized applications while preventing and mitigating modern security threats.

Keywords: Security, Kubernets, AI, ML

INTRODUCTION

Kubernetes has become one of the most relevant aspects in today's application deployment by providing efficient means of managing applications in containers. Since organizations implement Kubernetes to create elastic and reliable systems, security has emerged as an essential factor. The kind of structure that Kubernetes has like API Server, scheduler, Controller Manager, etc. makes cluster management easy, but at the same time if not security the whole cluster proves to be vulnerable.

Its distributed structure that depends on linked systems and integration with other applications increases it's a kind of attack. Some of the security concerns include avoidable typical ones like permissions and open ports in containers, and security issues due to containers' flaws, updated images and unsafe run-time configurations.

Furthermore, there is a network-level attack, unauthorized API server access, and supply chain attacks also add layers to the problem of Kubernetes security. Kubernetes environments are fluid and complex and that means that a pre-emptive approach to security is required that uses both elements of the platform and third-party tools and methods.

Kubernetes security threats and challenges can be comprehensively discussed in this paper, which reveals the threats organizations are exposed to and provides strategies that can address the issue. Analyzing the architectural structure, main risks, and protective measures will allow the work to equip the organizations with the knowledge on how to apply Kubernetes as securely and efficiently as possible while raising awareness about security issues around Kubernetes.

Kubernetes Architecture

Kubernetes, an open-source container scheduler, has changed the usual approach to application deployment in distributed topology. Kubernetes abstracts away the underlying infrastructure and offers a cohesive veneer through which to manage containerized applications, thus allowing its clientele – the developers and operators – to dedicate resources toward constructing robust and elastic systems.

Although its design involves a number of components and their complex interconnections, it has a number of problems in terms of security (Bhardwaj et al., 2024). To get a good perspective of Kubernetes, it is important to appreciate the fundamental elements of the container orchestration tool, its resource security framework and some the inherent issues of distributed systems.

The core component of Kubernetes is the master node: several elements in this node are critical in node management. The API Server acts as an interface or gateway through which users and external tools communicate to and with other

elements and it also relies on RESTful APIs. It opens an entry to the control plane and, therefore, has to be secured and properly protected when it comes to access and authentication.

Yet, the Scheduler's critical function is getting workloads, or Pods, scheduled on available nodes as well as according to some general policies. On the other hand, the Controller Manager is in charge of the synchronization between the current and the desired state of the cluster and is responsible for state management tasks including scaling, endpoint management and job completion.

In supporting the master node, there is the database, which contains all the cluster configuration data. Protection should be tight since unauthorized access will threaten the whole cluster. It is responsible for running containerized application workload, and it contains some components like kubernets to monitor that the containers are running properly, proxy to handle its networks traffic to, or from the PODs (Kampa, 2024). This post looks into each of these components and describes how they function as individual entities within Kubernetes while laying the ground for complexity that could lead to insecurity if combined improperly.

Container orchestration platforms such as Kubernetes have several security features that are already included to mitigate the risks corresponding to the containerized applications management. Role-Based Access Control (RBAC) is one of the key means of access control in the cluster's formation. RBAC, by binding roles to specific users or service accounts, can only be used to perform a certain number of actions strictly following the principle of least privilege.

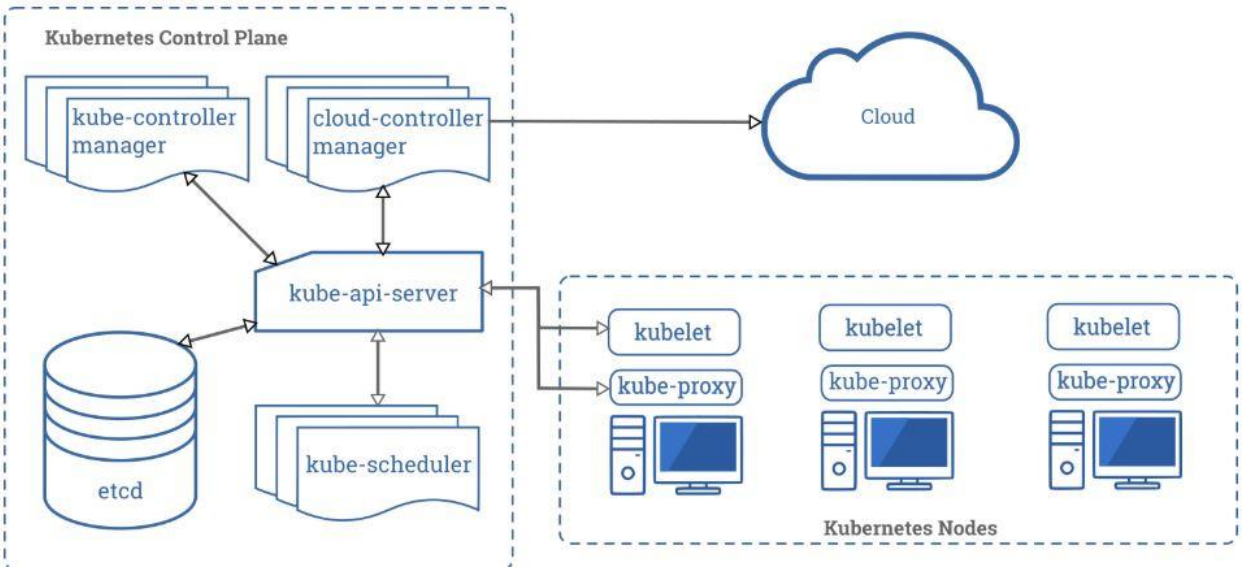

Figure 1Kubernets security flowchart (OWASP, 2024)

Pod Network Policies provide the means to manage traffic flow traverse to Pods and outside the cluster, thus such movement by attackers within the cluster (Tripathi, 2024). Furthermore, Managing Record has found out that Kubernetes also employs the concept of namespace to partition resources and workloads that are strategic in multi-tenanted systems.

Managing secrets for application-level credentials like API Keys WD-40 password and certificates is another enhanced property. Pods use Kubernetes Secrets to manage secret data to reduce the probability of such information leaking out to other unauthorized entities. Combined, these features form a strong foundation for the enforcement of policies and security but their strength is in the methods of management and updates that need to be applied.

However, these Kubernetes features make the security of Kubernetes clusters a challenging process, especially in a distributed setting. One of the primary challenges is, in fact, the complexity of Kubernetes itself, as a system with a huge number of options and possibilities. Its flexible architecture, although heavily fortified, brings a plethora of new settings which, if not properly controlled, create risks.

For instance, such uncontrolled work with RBAC might lead to the cases, where employees are granted overly permissive roles, or the access to the API Server of the cluster is not restricted properly, which means that the cluster may be opened to the users from the outside world. Likewise, standard configurations that opt for usability as opposed to security like employing insecure means of communication have to be changed to solve for security.

Securing these Kubernetes workloads is especially challenging given the inherent and dynamic nature of workloads inherent in Kubernetes (Curtis &Eisty, 2024). They are created and destroyed dynamically, that is pods and containers are scaled up and scaled down for load requirements which sometimes make it hard to have a fixed policy of managing the security vulnerabilities. Analogous to the situation with transaction management, monitoring and logging become yet another difficult problem, because by their very nature distributed systems are constantly changing, and traditional tools cannot cope with this.

Another great problem is to protect the network communications inside and outside the cluster. Kubernetes clusters are typically composed of multiple nodes located in different environments, in traditional buildings and at cloud service providers' facilities. Protecting communications between these nodes and the upper control plane is also significant in order to avoid leakage or other threat types.

Another network-level threat is man – in – the middle attack and traffic interception common in the distributed environment to warrant the use of transport layer security, TLS, VPN. Furthermore, the transformation to multi-cloud and hybrid has the effect of adding further complexity, in that organizations need to protect traffic in-between different networks and arrange. Adhering to the regulation also complicates the task, as data needs to be divided by categories and stored in certain locations.

The human factor also plays a tremendous role in exacerbating the security problems in Kubernetes. This introduces complexities to the structure that administrators and developers must learn about in order to avoid basic mistakes or oversights with the platform's configuration.

These difficulties are magnified by the relatively high rate of Kubernetes updates and the simultaneous addition of new features. To be successful, there are different complexities that organizations must manage, and, for this reason, organizations must invest in training and resources to build the teams.

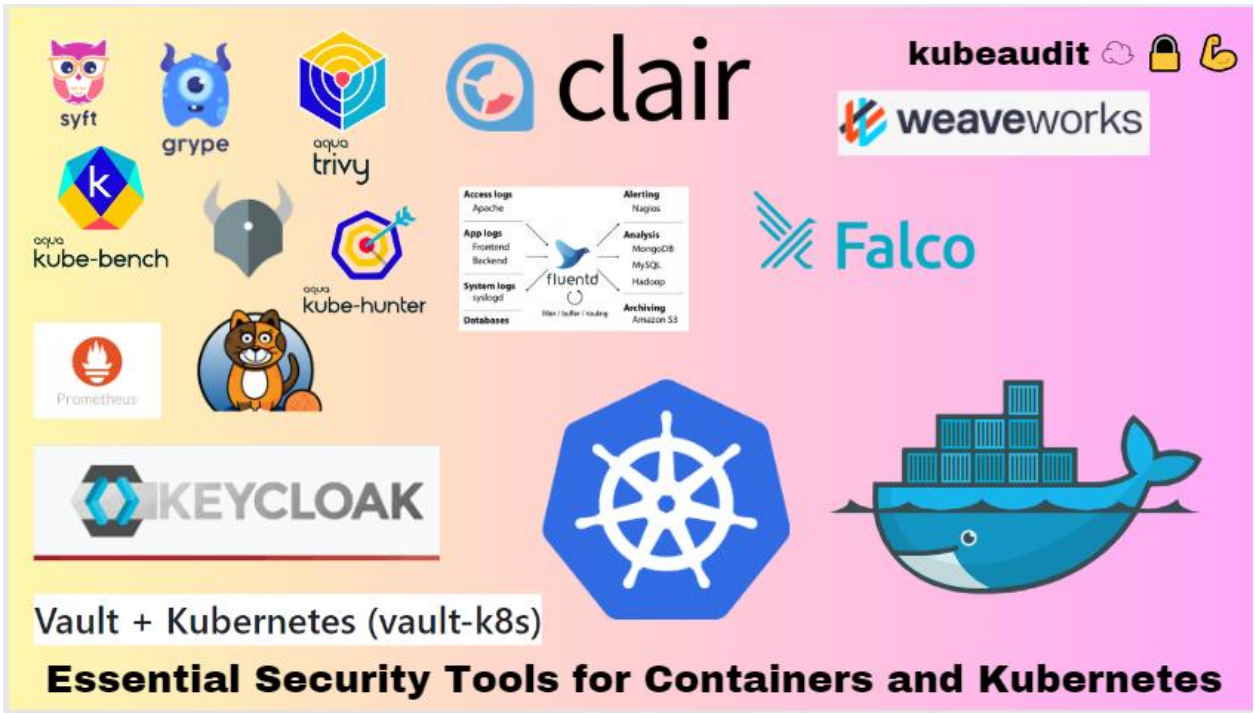

Figure 2 Security tools for Kubernets (Medium, 2023)

Furthermore, third-party plugins such as tools and extensions that are incorporated in Kubernetes environments, though improving functionality, pose a critical security risk (Donka et al., 2024). To ensure security each integration has to be checked for security threats, and updates to the service has to be controlled for newly known vulnerabilities.

Lastly, supply chain attacks remain a new challenge that stands out in Kubernetes ecosystems. Such attacks focus on all components utilized in the creation and deployment of containerized applications including but not limited to malicious container images or tainted CI/CD pipelines. To overcome this challenge, a good approach is to scan container images for vulnerability at a frequency and enforce strict measures on image sources and have tools that offer visibility in the

software supply chain. Moreover, changing the security paradigm to a zero-trust security system, where no component and users automatically receive trust, can also reduce the likelihood of supply chain threats.

Kubernetes and its security features give a strong background in managing carries applications in distributed conditions. However, the growth of the platform's functionality and such specific features of distributed systems as decentralization brings essential security concerns.

Thus, organizations face less risk by being familiar with the ingredients of Kubernetes and the potential of its integrated mechanisms for effective cybersecurity. Meeting these difficulties needs a technical approach, strict security measures and constant examination of the threats.

Key Security Threats

Kubernetes is a strong and rapidly growing platform for organizing the effective operation of containers, but this does not mean that it cannot encounter security issues. Perhaps one of the most prevalent security threats that originate from Kubernetes environments comes as a result of the misconfiguration of Kubernetes (Darwesh et al., 2024). These misconfigurations are due to the complexity of the structure and the flexibility of the number of options in tuning the Kubernetes.

A typical problem is when the authors simply set default parameters, which often grant "too many privileges" or include important elements that in fact should remain non-accessible. For instance, if RBAC has not been configured well, users or service accounts can access some resources they are not supposed to access and this will lead to a security vulnerable hold.

Likewise, failing to properly secure Kubernetes by not limitation to the level of Kubernetes API server or not properly configure network policies may leads to an attacker to gain unauthorized access or being able to move laterally in the cluster. These are exploited because the misconfigurations create opening through which attacker can get into the system and impact the workloads.

Making the problem worse, many organizations embrace Kubernetes hastily, and, thus, have critical shortcomings in security that villains can use. Another significant threat in Kubernetes is its exposure to threats that first affect the application itself when in a container.

After facing many container vulnerabilities from base images of the public registry images used in containers, they make them vulnerable of known vulnerabilities if checked and updated. Potential vulnerabilities of unpatched images are that it can be used as a starting ground for an attacker to take advantage of the existing vices and penetrate into the cluster. Additionally, it is a well-known fact that a container itself can be a source of vulnerabilities because the related container may contain outdated dependencies or poorly managed security updates.

There are still vulnerabilities at runtime when using secure images; for example, increasing the privileges within the container or insufficient isolation between containers on one node (Simonetto& Bosch, 2024). This risk is especially due to the fact that developers fail to adhere to successful implementations of least privilege principles, making containers to run as root or grant unnecessary privileges to the host OS.

Even when basic security measures have been implemented misconfigurations of these security elements can be used by the attackers to take over the container, move up the privilege level and infiltrate the entire Kubernetes cluster. Another kind of threat is network level threats since Kubernetes uses a highly interconnected network for its operations. The OSI flat network used in Kubernetes helps pods to communicate directly which is quite fast when moving from one pod to another, but it poses a significant threat such as DNS spoofing and traffic interception among others. In this attack, the attacker alters the process of resolving a Domain Name System to send traffic to another location, which could support eavesdropping and injection of other incorrect results.

In a similar vein, traffic interception attacks, for example, man-in-the middle (MITM) attacks are possible if communication between the components is unencrypted or unauthenticated. All these threats are especially concerning when the system serves multiple users or applications, all of which share the same cluster resources.

In a cluster, if there are no good network policies and no good policy for multitenant computation, the attackers can easily penetrate the system and can easily move from one node to another node and start attacking the sensitive workloads and sensitive data (Amgothu&Kankanala, 2024). The challenges of securing intra-cluster communication only escalate in the case where the environment is hybrid or multi-cloud in nature due to the difference in network structures and policies within the environments.

Another fundamental target is the Kubernetes API server which is an element of the platform. For it is the centralized point to interact with it as well as to perform certain management tasks, the API server contains access to such operations and resources.

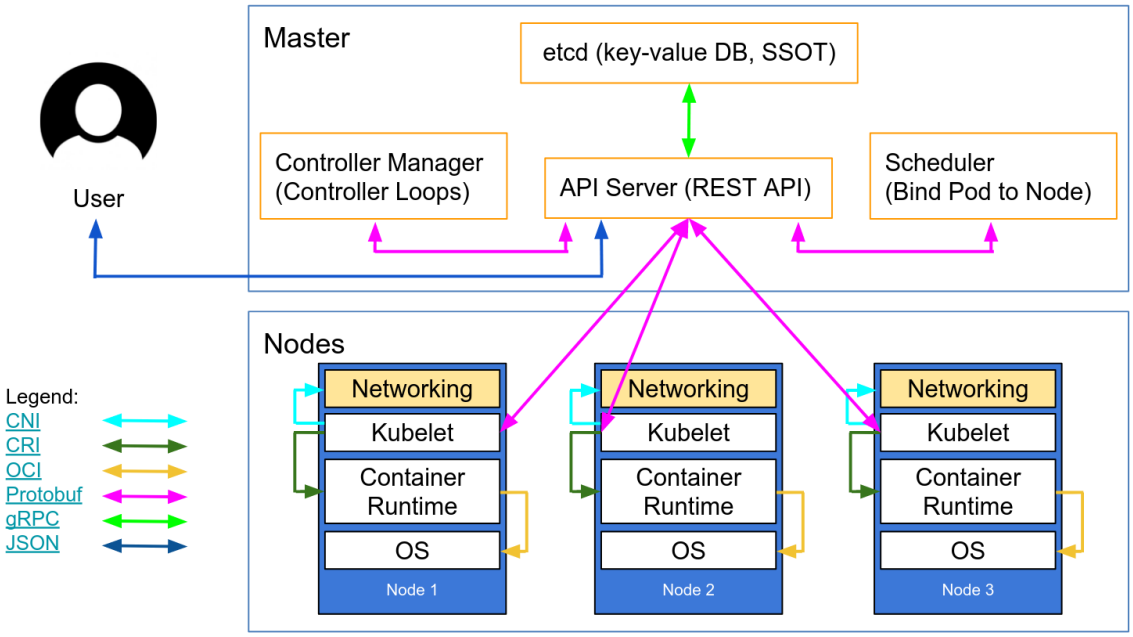

Figure 3 Kubernets security master guide (Rad Security, 2024)

Intruder access to the API server posess severe implications that let the attacker affect the Workloads, Data ex-filtration, and services disruptions. Some of the risks that are associated with the API server include the following; The API server normally faces threats because of poor authentication and poor authorization. For instance, incorporating weak credentials or releasing the API server to the internet without minimal security control restrains will allow the attackers to guess their way through the system.

However, having implemented the authentication, RBAC policies may be configured inadequately; this means that users and or applications are granted more than necessary privileges – thus are more vulnerable to exploitation (Klement et al., 2024). Another issue is the DoS attacks on the API server – here, an attacker sends many requests to the server with the aim of lowering the functionality of the cluster, or rendering it nonfunctional at all.

These threats can only be handled by reinforced and proper access control measures, adequate logging, and monitoring, periodic audit to check compliance with set standards. Supply chain attacks are an emerging and stealthy risk in Kubernetes environments and become severe as organizations leverage third-party components, images, and dependencies for developing and deploying their applications.

Due to the openness of supply chain, cyber criminals are able to inject malicious components into containers, plugins or libraries. For example, a stylized picture click from a public index might contain viruses that only start executing when loaded, giving the attackers a starting point in the cluster.

These attacks can also extend to CI/CD pipelines, where both builds and or dependencies are contaminated allowing for the spread of such weakness across the development lifecycle (Li et al., 2024). As kubernets work in close relations each other these attacks when manifested increase the severity to other workloads and or nodes of the cluster.

Trying to identify supply chain threats and prevent them is not an easy task because it involves extensive external parties' audits, constant monitoring of suspicious behaviour, and applying tools for identifying known vulnerabilities that concern images and code.

Table 1: Kubernetes security threats

Threat Category	Severity (1-10)	Frequency (% Incidents)	Mitigation Tool	Risk Level (High/Medium/Low)	Impact (1-100)
Misconfigurations	9	25%	RBAC Policies	High	80
	8	18%	Network Policies	High	75
Container Vulnerabilities	7	20%	Image Scanners	Medium	65
	9	12%	Pod Security Standards	High	85
Network Attacks	6	15%	CoreDNS Configurations	Medium	60
	8	10%	TLS Encryption	High	70
API Server Threats	10	20%	Strong Auth Mechanisms	High	90
	7	8%	Rate-Limiting Tools	Medium	65
Supply Chain Attacks	9	15%	Image Signing (Notary)	High	85
	8	10%	Secure CI/CD Tools	High	75
Secrets Management	8	17%	HashiCorp Vault	High	80
	7	10%	Secret Rotation Policies	Medium	65
Monitoring Gaps	6	15%	Fluentd/ELK Stack	Medium	60
	5	8%	Automated Alert Filters	Low	50

In this paper, Helm and Container Security are presented as the main threats to the majority of the aspects of Kubernetes architecture and business processes (Mycek&Łukaczyk, 2024). Configuration mistakes, security flaws of containers, network invasions, API server threats, and supply chain attacks are cardinal threats to the usefulness and dependability of Kubernetes platform.

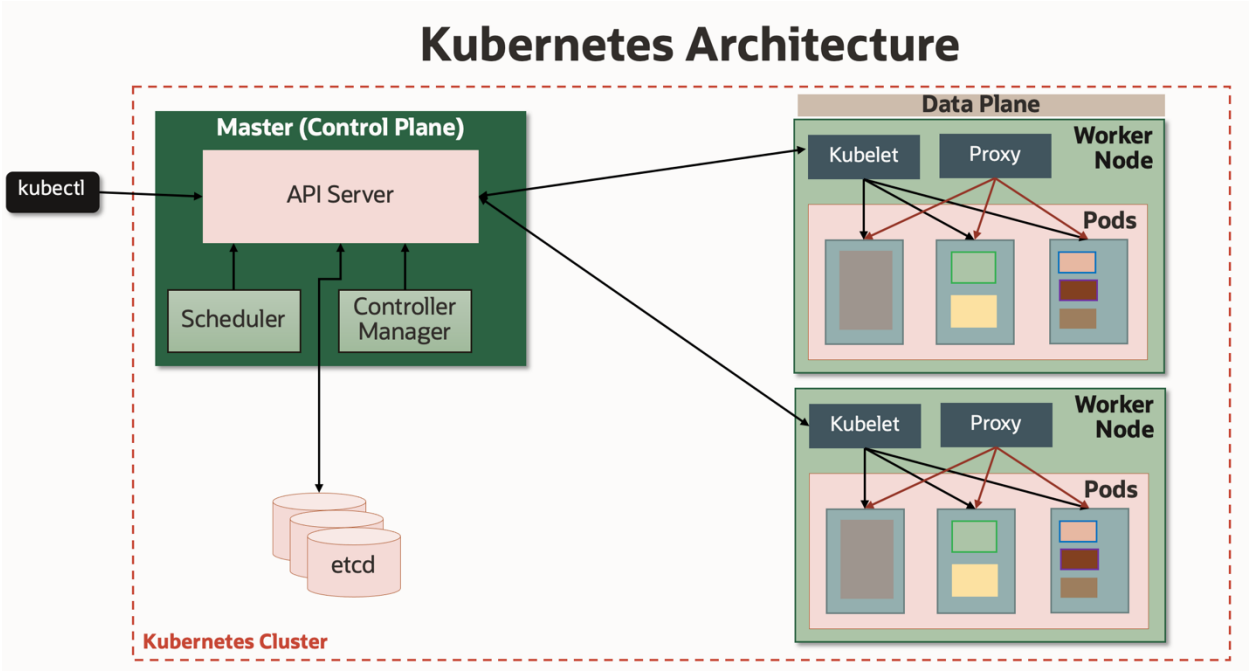

Figure 4Kubernets architecture (The New Stack, 2024)

All these threats make it imperative that organisations apply multiple layers of security that comprises of proper setting up of the systems, monitoring constantly and the application of security tools that would help in flagging off any

weaknesses (Wende, 2024). The community is still not equipped with the administrative tasks to operate Kubernetes securely, and the organizations that employ it need to focus on education, the promotion of Kubernetes security best practices, and continuous audit of the clusters to reduce the attack surface. Since the popularity of Kubernetes is only increasing, recognizing these threats will always be an important part of the effort to secure the cloud-native environment.

CONCLUSION

With Kubernetes being the market leader in the container orchestration space throughout the last couple of years, securing these environments is a critical requirement for organizations. This paper has explained the main parts of kubernetes architecture, from the API server through the scheduler and the controller manager as well as its security measures of Role-Based Access Control (RBAC), and Network Policies. All the same, Kubernetes is not invulnerable to risks as follows: Configuration-related issues, containers themselves, network-level threats, API server compromise, and supply chain issues represent key areas of cluster weakness and problematic areas.

It increases these risks with multiple folds especially in distributed environments, so organizational security has to be multi-layered and proactive. Other calamities include hardening the entry points, ensuring secure and encrypted communication, protect the container image and integrally observe cluster behaviors (Russell & Dev, 2024). This work especially highlights the need not to relax one's guard given that the threat actors could be changing tact especially with the increased adoption of kubernetes across various industries.

This paper gives an analysis of the architecture of Kubernetes, identification of various risks that are associated with it, and various measures that can be taken to combat the risks hence reducing the security risks when deploying containerized applications. The guidelines derived from the results of the present work will help businesses cement their security position and build trust in Kubernetes as the fundamental component of today's application stacks.

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