DEVELOPMENT OF ONTOLOGY BASED MULTITASKING MOBILE ROBOT SYSTEM: AN INDUSTRY 4.0 APPLICATION

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Master's Thesis
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Assoc. Prof. Dr. Barış ÖZYER
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(Ontoloji Tabanlı Çoklu Görev Mobil Robot Sisteminin Geliştirilmesi: Bir Endüstri 4.0 Uygulaması)

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This study, prepared by Sezer UĞUZ under the supervision of Assoc. Prof. Dr. Barış ÖZYER, was accepted by the following jury on 14/04/2023 as a Master of Science thesis in the department of Computer Engineering, on the field of Computer Engineering, with unanimous / majority of votes (.3./3.).

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To my lovely family

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ABSTRACT

MASTER'S THESIS

DEVELOPMENT OF ONTOLOGY BASED MULTITASKING MOBILE ROBOT SYSTEM: AN INDUSTRY 4.0 APPLICATION

Sezer UĞUZ

Advisor: Assoc. Prof. Dr. Barış ÖZYER

Purpose: This thesis has two aims, first to develop a solution to the large productivity losses in the production stage of the smart factory environment with the aid of mobile robot technology, one of the Industry 40 applications. In accordance with the standart scenarios, the objective is for the mobile robot to reach the targets accurately and carry out the tasks at the most affordable cost. The second aim is to observe the research trends in respect of mobile robots, which hold an important place in Industry 4.0 applications. In this endeavour, topic modeling and bibliometric analyses were carried out.

Method: The present thesis develops a new framework named Ontology Based Mobile Robot System for Industry 4.0 (OMRi40) which can be used in Industry 4.0 applications. This framework consists of three main layers: Cloud Computing Services, Ontology and Algorithm, and Simulation Environment. Cloud Application Tools, Firebase Realtime Database, Apache Jena Fuseki, and Python were used in the Cloud Computing Services part of the OMRi40. OWL Ontology, Multi-task Planning Algorithm and Task Planning Algorithm were created in Ontology and Algorithm part of the OMRi40. The Simulation Environment section of the OMRi40 was built using CoppeliaSim software. Topic modeling analyses were carried out using both LDA and LDA with the MALLET model for both periods of the study. Python programming language was used in all analyses of the study. Topic modeling analyses were carried out using both models for both periods: the LDA with MALLET model gave better results than LDA model for both periods. The LDA with MALLET model was selected for analyses in this study. Google Colaboratory was preferred as integrated development environment (IDE) for Python. Natural Language Toolkit (NLTK), LDA and MALLET libraries were used in the topic modeling (text mining) phase, Pandas and Numpy libraries for bibliometric analysis, and Matplotlib and Plotly libraries for data visualization.

Findings: The testing phase of the OMRi40 framework was completed successfully. RFID and QR code tags were successfully read by the sensors (RFID and QR code readers) integrated into the simulation environment of the mobile robot and communicated to the cloud computing services. During the multi-tasking of the mobile robot, the target points that the mobile robot should go to first were established by the task priority algorithm and ontology. Topic modeling and bibliometric analyses were examined in detail. The top five research topics that came to the fore in each of the two periods were observed. Image Recognition and Object Detection, Localization Sensors, Path Planning Algorithm and Trajectory Motion Control were among the popular research topics that come into prominence in both periods. Regarding the top five most cited research topics for the two periods, the most striking situation here is that the Path Planning Algorithm research topic is in first place in terms of the number of citations in both periods. It is also noteworthy that the research topic Automated Guided Vehicles in Industry emerged in the second period as one of the most cited research topics. In addition, the top five most productive countries for both periods were analyzed. When the productivity of the countries with which the authors' academic studies are affiliated were examined, China and the United States were seen to have risen to prominence by taking first and second places in both periods. India did not figure in the first period, but did so in the second period, and as such was the country that attracted attention.

Results: The OMRi40 Framework developed within the scope of this thesis has been tested on dummy data using wo different usage scenarios with the same task list. Both QR Code Scanner and RFID Tag Reader, were tested. According to these results, data transactions made with QR Code Scanner were faster in seconds compared to RFID Reader. The results of these analyses are included as a part of this thesis and can contribute to future studies as a guide. These analyses revealed the current research trends in the field of mobile robots, so that it can be said that the present study sheds light on future prospects in this field.

2023, 74 pages

Keyword: Mobile Robot, Industry 4.0, Smart Factory, Textile Manufacturing, Multi-Tasking, Path Planning, Ontology, Cloud Computing, Algorithm, Topic Modeling, Data Analysis

ÖZET

YÜKSEK LİSANS TEZİ

ONTOLOJİ TABANLI ÇOKLU GÖREV MOBİL ROBOT SİSTEMİNİN GELİŞTİRİLMESİ: BİR ENDÜSTRİ 4.0 UYGULAMASI

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Amaç: Bu tezin iki amacı vardır; birincisi akıllı fabrika ortamının üretim aşamasındaki büyük verimlilik kayıplarına Endüstri 40 uygulamalarından biri olan mobil robot teknolojisi yardımıyla bir çözüm geliştirmek, ikincisi ise Endüstri 4.0 uygulamalarında önemli bir yer tutan mobil robotlarla ilgili araştırma eğilimlerini gözlemlemektir.

Endüstri 4.0 uygulamalarının gelişmesiyle birlikte tekstil fabrikalarının ulusal ve uluslararası pazarlarda rekabet güçlerini sürdürebilmeleri için üretim süreçlerinin yüksek verimliliğe ve kısa değişim sürelerine sahip olması gerekmektedir. Bu rekabetin en önemli kriteri zaman kaybını minimuma indirirken verimliliği maksimuma çıkarmaktır. Üretim hatlarındaki ürün parçalarının bir araya getirilerek dikildiği dikim atölyesi, tekstil üretiminde uygulanan iş akış sürecinin en önemli aşamalarından biridir. Dikim atölyesinde verimlilik ve zaman kayıplarına neden olan en önemli etkenlerden biri de depodan üretim hattına getirilen çeşitli ürün aksesuarlarının teslimidir. Bu aksesuarların (düğme, etiket vb.) zamanında depodan temin edilememesi, bir tekstil fabrikasının dikim atölyesi bölümündeki rutin işleri aksatmakta ve üretim hatlarındaki operatörler dikişi teslim almadığında önemli ölçüde zaman kaybedilmektedir.

Bu tezin ilk amacı, Endüstri 4.0 uygulamalarından biri olan mobil robot teknolojisi ile fabrika ortamındaki büyük verimlilik kayıplarına çözüm geliştirmektir. Böylece kullanım senaryolarına uygun olarak mobil robotun hedeflere doğru bir şekilde ulaşması ve görevleri en uygun maliyetle gerçekleştirmesi amaçlanmaktadır. Ontoloji ile Endüstri 4.0 uygulamalarının bir parçası olan Nesnelerin İnterneti (IoT), Bulut Bilişim ve Mobil Robot, bu çalışmada rol oynayan dört ana unsurdur. IoT sayesinde mobil robot, çevresiyle veri alışverişi yapabilir ve iletişim kurabilir. Çoklu görev yapabilen mobil robot, aksesuar stoğundaki malzemelerin dikim atölyesine getirilmesinden kaynaklanan zaman kaybının önüne geçilmesini mümkün kılmaktadır. Mobil robot sisteminin fabrika ortamındaki görevler için bulut bilişimde oluşturulan görev önceliği (öncelik faktörü) algoritmasını kullanarak en uygun rotaları seçerek verilen görevleri en iyi şekilde gerçekleştirmesi tezin en önemli amaçlarından bir tanesidir. Bu amaç doğrultusunda, mobil robotun hareket planının oluşturulması ve karar destek sistemine bağlı olarak mevcut görevin yerine getirilmesi aşamasında ontoloji tabanlı bir anlamsal yapı geliştirilmiştir. Bu, tekstil fabrikası ortamında çok görevli bir mobil robot sistemi için yenilikçi bir yaklaşımdır. Mobil robotun sorumlu olduğu çoklu görevlerin yerine getirilmesi, yapılan işlemlerin IoT üzerinden bulut bilişim sistemine raporlanmasını ve görevlerin tamamlanmasını sağlar.

Bu tez çalışmasının ikinci amacı ise Endüstri 4.0 uygulamalarında önemli bir yer tutan mobil robotlarla ilgili araştırma eğilimlerini gözlemlemektir. Mobil robotlar, robotik alanda yapılan çalışmaların başında gelmektedir. Hem akademik olarak hem de endüstri alanında teorik ve uygulamalı çalışmaların yapıldığı mobil robot alanına olan ilgi her geçen gün daha da artmaktadır. İlk kez Alman konsorsiyumu tarafından 2011 yılında Hannover Fuarı'nda sunulan Endüstri 4.0 terimi, Avrupa ülkelerinin sanayideki üretim süreçlerinde meydana gelen zorluklara yeni nesil çözümler üretmek ve teknolojik düzeyini artırmak için yeni bir devrin

başlamasına yol açmıştır. Dördüncü sanayi devrimi olarak da bilinen endüstri 4.0, bulut bilişim, siber-fiziksel sistemler, büyük veri, nesnelerin interneti ve otonom robotlar dahil olmak üzere dokuz ana teknoloji bölümünden oluşur. Gelişen teknolojilerle birlikte endüstriyel ortamlardaki cihazlar arasında kablosuz iletişim büyük önem kazanmıştır ve bu sayede cihazlar arasında bilgi alışverişi daha hızlı gerçekleşerek üretim süreçleri daha verimli ve akıllı hale gelmiştir. Endüstri 4.0'ın ortaya çıkmasıyla birlikte günümüze kadar birçok akademik çalışma gerçekleştirilmiştir. Buna ek olarak, endüstri 4.0 çerçevesinde yazarların yapmış olduğu yayınların performansını, kavramsal gelişimini ele almak ve gelecekteki araştırmaların içgörülerine ve bakış açılarına katkı sağlamak için Scopus veri tabanı kullanılarak birtakım bibliyometrik çalışmalar yer almaktadır. Ayrıca yapılan çalışmaların birinde endüstri 4.0 alanında yapılan çalışmaların kuantumunun her yıl 2 kat arttığı gözlemlenmiştir.

Yöntem: Tezin ilk amacı için bu bölümde, Endüstri 4.0 için Ontoloji Tabanlı Mobil Robot Sistemi (OMRi40) oluşturulmuştur. Bu sistem, OMRi40 için Bulut Bilişim Hizmetleri, OMRi40 için Ontoloji ve Algoritma ve OMRi40 için Simülasyon Ortamı olmak üzere 3 başlık altında ele alınmıştır. OMRi40 için Bulut Bilişim Hizmetleri (CCS) dört alt başlık altında toplanmıştır. Bunlardan ilki, dikiş makinesi operatörlerinin malzeme istekleri için bir kullanıcı arayüzüne sahip olan OMRi40 için Bulut Uygulaması'dır. İkinci alt başlık, bulut uygulama verilerinin saklandığı OMRi40 için Gerçek Zamanlı Veritabanı'dır. Bunların üçüncüsü, mobil robotun mevcut görevini sorgulamak için RDF (Resource Description Framework) üçlü görevlerini depolayan OMRi40 için Apache Jena Fuseki'dir. Dördüncü ve son alt başlık, hem Gerçek Zamanlı Veritabanı hem de Apache Jena Fuseki ile iletişim kuran OMRi40 için Python Betik Dosyaları'dır.

OMRi40 için Bulut Bilişim Hizmetleri bölümünde tekstil atölyesinde çalışanların malzeme gereksinimleri bulut uygulaması üzerinden kayıt altına alınmıştır. Bulut uygulaması HTML (HyperText Markup Language), JS (JavaScript), CSS (Cascading Style Sheets), PHP (Hypertext Preprocessor) ve MySQL bileşenlerinden oluşmaktadır. Bu bulut uygulamasına erişim, tekstil atölyesinin üretim hatlarında bulunan tabletler üzerinden sağlanmaktadır. Kullanıcıdan istek bilgisi olarak Malzeme Cinsi, Malzeme Cinsi Detayı ve Miktar bilgileri alınmıştır. Bunlara ek olarak bulut uygulamasının arka yüzünde Zaman Damgası, Analiz Edildi Mi, Malzeme Öncelik Değeri, Kişisel Kimlik, Üretim Hattı Noktası verileri oluşturulmuş ve OMRi40 sistemindeki çoklu görev analizleri için Gerçek Zamanlı Veritabanı'na kaydedilmiştir. OMRi40 için Gerçek Zamanlı Veritabanı bölümünde ise Firebase Gerçek Zamanlı Veritabanı kullanılmaktadır. Gününümüz teknolojisinde, endüstri fabrikalarının veya şirketlerinin çeşitli bulut uygulamaları, NoSQL veri depolamanın buluta aktarılabilmesi ve hızlı veri erişimini destekleyebilmesinden dolayı popüler olan "Not Only SQL" (NoSQL) kullanılmaktadır. Bu tezin kullanım senaryosu, Endüstri 4.0 yetkinlikleri ile büyük veri üreten akıllı bir tekstil fabrikasını içermektedir. Dolayısıyla NoSQL veritabanı, buluta anlık veri aktarımı özelliği, bulutta veri okuma ve yazma işlemi ve iç içe geçmiş veri yapısı ile bu çalışma için oldukça kullanışlıdır. Bu çalışmada Firebase Realtime Database (RTDB) kullanılmış ve OMRi40 için OMRi40_RTDB adında bir veritabanı oluşturulmuştur. OMRi40 için Apache Fuseki Server bölümünde ise bir SPARQL (SPARQL Protocol and RDF Query Language) sunucusu olan Apache Jena Fuseki yer almaktadır. Apache Jena Fuseki, http (Hypertext Transfer Protocol) üzerinden çeşitli SPARQL sorgularının RDF verilerine erişmesini sağlar. Fuseki, RDF verilerini depolamak ve sorgulamak için üçlü bir mağaza yapısına sahip olan Jena'nın bir bileşeni olan TDB ile sıkı bir şekilde entegredir. TDB'nin tek bir makine üzerinde yüksek performanslı bir RDF deposu olarak kullanılabileceği belirtilmiştir. OMRi40 için Python Betiği bölümünde, Python programlama dilinde yazılan betikler yer almaktadır. Bu betikler, OMRi40 çatısı içinde önemli bir yere sahiptir. Python, firebase_admin ve SPARQLWrapper kitaplıklarını kullanarak hem Firebase Gerçek Zamanlı Veritabanı hem de Apache Fuseki Sunucusu tarafından veri alışverişi sağlar. Ayrıca bu verilerin analizini yaparak görevleri sırasıyla mobil robota iletir. OMRi40 için Ontoloji ve Algoritma bölümünde ise geliştirilen

OWL modeli, Çoklu Görev Yol Planlama ve Görev Önceliği algoritmaları yer almaktadır. OMRi40 için Simülasyon Ortamı bölümünde ise mobil robotun başlangıç noktasından hedef noktaya örnek bir yolculuğu oluşturulmuştur.

Konu modelleme ve bibliyometrik analiz çalışmasında Scopus veri tabanında yayımlanmış mobil robot alanındaki 13404 adet makale ele alınmıştır. Son 20 yıldaki (2002-2021) ele alınan bu makalelerde, Endüstri 4.0 kavramının ortaya çıktığı 2011 yılının öncesinde ve sonrasındaki hem akademik camianın hem de sanayide yapılan teorik ve uygulamalı çalışmaların ne yöne evrildiği, nasıl değişiklik gösterdiği ve hangi eğilimlerin öne çıktığı incelenmiştir. Böylelikle Endüstri 4.0'ın yanı sıra gelişen teknolojiyle birlikte mobil robot alanındaki yol planlama, navigasyon ve görev planlama gibi temel araştırma konularında meydana gelen değişimler konu modelleme tekniğiyle gözlemlenmiştir. Buna ek olarak LDA (Latent Dirichlet Allocation) MALLET (Machine Learning for Language Toolkit) modelleriyle oluşturulan konu modelleme başlıklarının atıf dağılımı da eklenerek araştırmaların ne yönde ilgi çektiği incelenmiştir. Bu çalışma Konu Modelleme, Bibliyometrik Analiz ve Metin Madenciliği bileşenlerini içermektedir.

Bu çalışma kapsamında toplanan makaleler içerisinden sadece Konferans bildileri ve Dergi makaleleri ele alınmıştır. Bunun için uygulanan filtreleme sonucunda geriye 13414 adet makale kalmıştır. 13414 adet makalenin Başlık ve Özet sütunlarında eksik veri (nan value) olup olmadığına bakılmıştır. Daha sonrasında Başlık ve Özet sütunlarında tekrarlayan aynı makalelerin olup olmadığı kontrol edilmiştir. Aynı olan makale bilgilerinin kaldırılması sonucunda geriye 13404 adet makale kalmıştır. 2002-2011 yılları arasında 3556'sı Konferans bildirisi ve 1131'i Dergi makalesi olmak üzere toplam 4687 adet makale mevcuttur. 2012-2021 yılları arasında ise 5775'i Konferans bildirisi ve 2942'si Dergi makalesi olmak üzere toplam 8717 adet makale mevcuttur. Bu bilgiler ışığında, son 10 yıldaki makale sayısının önceki 10 yıla göre yaklaşık 2 kat arttığı görülmektedir.

Endüstri 4.0 Devrimi'nin 2011 yılında ortaya çıkmasıyla birlikte mobil robotların kullanım alanları daha da genişlemiştir ve bu alanda yapılan hem akademik hem de endüstrideki Araştırma&Geliştirme çalışmaları gün geçtikçe artmaya başlamıştır. Bu çalışma Konu Modelleme, Bibliyometrik Analiz ve Metin Madenciliği analizlerinden oluşmaktadır ve analizlerin çıktıları bu makalenin Sonuçlar kısmında detaylı olarak yer almaktadır. Bu çalışmanın bütün analizlerinde Python programlama dili kullanılmıştır. Python için tümleşik geliştirme ortamı (IDE) olarak Google Colaboratory adlı web IDE'si tercih edilmiştir. Konu modelleme aşamasında LDA ve MALLET kütüphaneleri, bibliyometrik analiz kısmında Pandas ve Numpy kütüphaneleri, metin madenciliği aşamasında Natural Language Toolkit (NLTK) kütüphanesi ve veri görselleştirme kısmında ise Matplotlib ile Plotly kütüphaneleri kullanılmıştır.

Bulgular: Tezin bu bölümünde, geliştirilen OMRi40 çerçevesinin testleri yapılmıştır. Testler, Endüstri 4.0 konseptinde bir akıllı tekstil fabrikası için geliştirilen kullanım senaryolarından oluşmakta ve OMRi40 çerçevesinin simülasyon ortamında çalışır hale getirilmesi için sağlanmıştır. Simülasyon ortamının geliştirilmesi halen devam etmektedir. OMRi40 çerçevesinin simülasyon ortamı stabilize edildikten sonra gerçek bir mobil robot ortamında da test edilecektir. Bu tez kapsamında geliştirilen OMRi40 çerçevesi, yapay veriler üzerinde test edilmiştir. Aynı görev listesinin, QR Code Tarayıcı ve RFID Etiket Okuyucu'nun iki farklı kullanım senaryosu uygulanmıştır. Bu sonuçlara göre QR Code Tarayıcı ile yapılan veri işlemleri RFID Etiket Okuyucu'ya göre saniye bazında daha hızlı gerçekleşmiştir. İşlem süresi +/- %10'luk bir hata payı içermektedir.

Bu tezin konu modelleme ve bibliyometrik analiz kısmında LDA ve LDA MALLET modelleri oluşturulmuştur. Bu modellerin tutarlılık değerlerinin sonucuna göre her iki dönem için de LDA MALLET modelinin tutarlılık değerleri daha iyi sonuç vermiştir. Bu analizler, Endüstri 4.0'ın ortaya çıktığı 2011 yılı göz önüne alınarak gerçekleştirilmiştir. 2002-2011 ve 2012-2021 olarak iki 10 yıllık zaman diliminde incelenmiştir. Her iki dönemde de 10 ortak konunun olduğu görülmektedir. Bu konular şunlardır: Sinir Ağı Öğrenme, Arazi Ortamında Mobil Robot, Yörünge Hareket Kontrolü, Otonom Araç Geliştirme, Maliyet ve Verimlilik Problemleri, Mobil Robotların Engel Ortamları, Otonom Mobil Robot Navigasyonu, Konumlandırma Sensörleri, Görüntü Tanıma ve Nesne Tespiti ve Yol Planlama Algoritması. 2002-2011 periyodunda yer alan ancak 2012-2021 periyodunda yer almayan konular şunlardır: Çevre Haritalama ve İç Mekan Lokalizasyonu, Mobil Robot Lokalizasyonu için Genetik Algoritmalar, Mobil Robotta İnsan Robot Haberleşmesi ve Endüstriyel Uygulamalar. 2002-2011 periyodunda yer alan ancak 2012-2021 periyodunda yer almayan konular ise şunlardır: Mobil Robotik Sistemlerin Yazılım Mimarisi, İç Ortamlar için Semantik SLAM (Simultaneous Localization and Mapping), Mobil Robotta İnsan Robot Etkileşimi, Robotik Etmenlerde Çoklu Görevler, Verimlilik Algoritmaları ve Endüstride Otomatik Yönlendirmeli Araçlar.

2012-2021 periyodunda yeni araştırma konuları oldukça ilgi çekici görünmektedir. Bununla beraber Endüstride Otomatik Yönlendirmeli Araçlar ile ilgili çalışmaların yeni bir trend olarak artması muhtemel görünmektedir. Çünkü bu yeni akım son 10 yılda gündeme gelmiştir. Ayrıca bu yeni trend, ilk 10 yıllık dönemde 4. sırada yer alan Yörünge Hareket Kontrolü yerine 4. sırada yer almıştır. Endüstri 4.0 ile birlikte ortaya çıkan akıllı fabrika dönüşümünün, Endüstride Otomatik Yönlendirmeli Araçlar'ın ön plana çıkmasında önemli bir faktör olduğu ifade edilebilir. Bununla birlikte yine son 10 yıllık dönemde Yol Planlama Algoritması adlı konu ilk sıraya yerleşmiştir. Bu konunun ilk sıraya yükselmesinde Endüstride Otomatik Yönlendirmeli Araçlar konusuyla ilgili yapılan çalışmaların katkısı olduğu belirtilebilir. Çünkü otomatik yönlendirmeli araçların iş akışındaki görevleri yerine getirebilmesi için en uygun güzergaha sahip olması gerekmektedir. Bu nedenle otomatik yönlendirmeli araçlarr için yol planlama önemli bir yere sahiptir.

Bibliyometrik analiz ile 2002-2011 ve 2012-2021 dönemleri arasında araştırma konularına, yazarlara, kurumlara ve ülkelere ilişkin çeşitli sonuçlara ulaşılmıştır. Bu analiz sonuçları, mobil robot alanında yapılan çalışmalar ile ilgili önemli görüşler sunmaktadır. Özellikle atıf sayıları bilimsel yayınların ön plana çıkmasında önemli bir rol oynamaktadır. İlk dönemde en yüksek atıf sayılarına sahip ilk 3 baskın araştırma konusu sırasıyla Yol Planlama Algoritması, Ortam Haritalama ve İç Mekan Lokalizasyonu, Görüntü Tanıma ve Nesne Tespiti'dir. İkinci dönemde en yüksek atıf sayılarına sahip ilk 3 baskın araştırma konusu ise sırasıyla Yol Planlama Algoritması, Görüntü Tanıma ve Nesne Tespiti ve Konumlandırma Sensörleri olmuştur. Ayrıca her iki döneme ait en üretken ilk 5 yazar tespit edilmiştir. İlk dönemdeki yazarlar sırasıyla Yang S. X., Burgard W., Parhi D. R., Siegwart R., ve Savkin A. V.'dir. Son dönemdeki yazarlar ise sırasıyla Parhi D. R., Mohanty P.K., Savkin A. V., Burgard W. ve Chung W.'dir. Burgard W., Parhi D.R. ve Savkin A.V. her iki dönemde de yer almayı başarmıştır. Buna ek olarak her iki döneme ait en üretken ilk 5 ülke incelenmiştir. İlk dönemdeki üretken ülkeler sırasıyla Çin, ABD, Japonya, Güney Kore ve Almanya'dır. Son dönemdeki üretken ülkeler ise sırasıyla Çin, ABD, Hindistan, Almanya ve Japonya'dır. Çin ve ABD sırasıyla 1. ve 2. sıradaki yerlerini korumuştur. Hindistan'ın son 10 yıldaki yükselişi ise oldukça dikkat çekmektedir.

Sonuç: Bu tez çalışmasında, Endüstri 4.0 uygulamalarında kullanılabilecek, Endüstri 4.0 için Ontoloji Tabanlı Mobil Robot Sistemi adlı yeni bir çerçeve geliştirilmiştir. Bu çerçeve, Bulut Bilişim Hizmetleri, Ontoloji ve Algoritma ve Simülasyon Ortamı ana katmanlarından oluşmaktadır. OMRi40 çerçevesinin test aşaması başarıyla tamamlanmıştır. RFID (Radio Frequency Identification) ve QR (Quick Response) kod etiketleri, mobil robotun simülasyon ortamına entegre edilen ve bulut bilişim servislerine iletilen sensörler (RFID ve QR kod okuyucular) tarafından başarıyla okunmuştur. Mobil robotun çoklu görevleri sırasında, mobil robotun ilk gitmesi gereken hedef noktalar, görev öncelik algoritması ve ontolojisi ile oluşturulmuştur.

OMRi40 çerçevesi, mobil robot ve dikiş atölyesindeki personel tarafından anlık verilerin üretilmesine ve kaydedilmesine olanak tanır. İşlenen veriler, Python betikleri kullanılarak analize hazır hale gelir. Verilere Görev Önceliği algoritması uygulanır ve veriler Fuseki Sunucusunda tutulur. Mobil robotun bir sonraki görev talebi doğrultusunda Çoklu Görev Yol Planlama algoritması kullanılarak RDF sorgusu çalıştırılır ve mevcut yol bilgisi sunulur. Tüm bu işlemler OMRi40 çerçevesi tarafından test edilmiş ve başarıyla gerçekleştirilmiştir.

Bu tez çalışmasında üç sınırlama mevcuttur. Bunlardan ilki, geliştirilen OMRi40 çerçevesinin gerçek bir veri seti ile test edilmemiş olmasıdır. Veri seti gerçek olsaydı, OMRi40'taki algoritmaların hem etkinliği hem de kullanımı, kullanım senaryolarına bağlı olarak daha iyi test edilebilirdi ve OMRi40 çerçevesinin performansı çok sayıda görev üzerinde test edilebilirdi. İkinci sınırlama, kullanılan kullanım senaryolarının dikiş atölyesinde yalnızca bir mobil robotun test edildiğini dikkate almasıdır. Hedef noktalara ulaşmak için çoklu mobil robotlar tarafından çoklu görevlerin paylaşılması bu çalışmada gerçekleştirilmemiştir. Üçüncü sınırlama, görevler yerine getirilirken yol planlamasının dinamik olması yerine statik bir şekilde gerçekleşmesidir. Mobil robot görevlere başlamadan önce görev listesi analiz edilmiş ve görev öncelik algoritmasına göre sıralanmıştır. Mobil robot göreve başladıktan sonra dikiş atölyesinde okuduğu her etiket için öncelik algoritması tekrar tekrar hesaplanmamaktadır. Bu nedenle mobil robot başlangıç noktasından hareket etmeye başladığı andan itibaren görevleri statik olarak yerine getirmektedir.

Gelecekteki çalışmalarda, OMRi40 çerçevesi kullanılarak, algoritmaların gerçek görev veri setleri ile kullanılması, simülasyon ortamında kullanım senaryolarının oluşturulması ve gerçek dünyada yer alan çoklu mobil robotlara uygulanması planlanmaktadır. Ayrıca mobil robotun statik olarak gerçekleştirdiği görevler dinamik hale getirilebilir. Bu durum, görevlerin statik ve dinamik gerçekleştirilmesindeki oluşabilecek farklılıkların gözlemlenmesini sağlayacaktır. Zamanla büyük veriye dönüşecek olan gerçek görev veri setlerine uygulanabilecek makine öğrenmesi algoritmaları ile görev sürecinin tamamlanma süresi tahmin edilebilir. Bu da Endüstri 4.0 konseptinde akıllı fabrikaların üretim aşamalarında verimliliğin artırılmasına ve zaman kaybının en aza indirilmesine katkı sağlayabilir.

Konu modelleme çalışmasında Scopus veri tabanından toplanan 13404 adet makalenin özeti, 2002-2011 ve 2012-2021 yılları arasında 10 yıllık periyotlar halinde iki dönem olarak ele alınmıştır. Endüstri 4.0'ın ortaya çıktığı 2011 yılı bir dönüm noktası olarak belirlenmiştir. Bu nedenle endüstri 4.0 kavramının ortaya çıkmadan önceki ve sonraki zaman içerisinde mobil robot alanında yapılan çalışmaların hangi doğrultuda ilerlediği ve ne gibi değişiklikler meydana geldiği incelenmiştir. Elde edilen analizler sonucunda mobil robot alanında yapılan çalışmaların endüstri 4.0 alanında meydana gelen gelişmelerle ilişkili olduğu gözlemlenmiştir. Bu çalışmadaki analiz sonuçları ışığında araştırma sorularına cevaplar verilmiştir.

Öncelikle bu çalışmada her iki dönem için LDA MALLET modeli kullanılarak konu modelleme analizleri ortaya çıkarılmıştır. Her iki dönemde öne çıkan ilk 5 araştırma konusu incelenmiştir. Görüntü Tanıma ve Nesne Tespiti, Konumlandırma Sensörleri, Yol Planlama Algoritması ve Yörünge Hareket Kontrolü konuları her iki dönemde de öne çıkan popüler araştırma konuları arasında yer almıştır. Buna ek olarak Endüstride Otomatik Yönlendirmeli Araçlar adlı araştırma konusu ikinci periyotta ön planda yer almasının sebebi endüstri 4.0'ın ortaya çıkması ile meydana gelen gelişmelerden kaynaklandığı söylenebilir. Bu nedenle bu araştırma konusu oldukça göze çarpmaktadır. Endüstride Otomatik Yönlendirmeli Araçlar ile birlikte ilk dönemde yer almayıp ikinci dönemde yer alan Mobil Robotik Sistemlerin Yazılım Mimarisi, Kapalı Ortamlar için Semantik SLAM, Mobil Robotta İnsan Robot Etkileşimi, Robotik Etmenlerde Çoklu Görevler ve Verimlilik Algoritmaları araştırma konuları da son 10 yıllık periyotta öne çıkan yeni trendler olarak belirtilebilir.

Her iki döneme ait en çok atıf alan ilk 5 araştırma konusu incelenmiştir. Burada dikkat çeken en önemli durum ise Yol Planlama Algoritması araştırma konusunun her iki dönemde de atıf sayısında ilk sırada yer alması olarak belirtilebilir. Ayrıca Endüstride Otomatik Yönlendirmeli Araçlar araştırma konusunun ikinci periyotta ortaya çıkması ve en çok atıf alan araştırma konularından biri olması dikkat çekmektedir. Her iki dönemde de çalışmalarıyla ön plana çıkan yazarlar Burgard W., Parhi D. R. ve Savkin A. V.'dır. Parhi D. R. son 10 yıllık dönemde mobil robot alanında yaptığı çalışmalarla ön plana çıkmıştır. Ayrıca her iki döneme ait en üretken ilk 5 ülke de incelenmiştir. Burada yazarların akademik çalışmalar yapmakta olduğu kurumların bağlı olduğu ülkelerin üretkenliği ele alınmıştır. Bunun sonucunda her iki dönemde de Çin ve ABD sırasıyla birinci ve ikinci sırada yer alarak ön plana çıkmıştır. Buna ek olarak Japonya ve Almanya da her iki dönemde yer almayı başarmıştır. Hindistan ilk dönemde olmayıp ikinci dönemde yer alarak dikkat çeken ülke olmuştur.

Bu çalışmada endüstri 4.0 öncesi ve sonrası çerçevesinde mobil robot alanındaki araştırma konularının ne yöne evrildiği incelenerek bu alanda gelecek çalışmalar yapacak olan akademi ve endüstri camiası ile paylaşılmıştır.

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Anahtar Kelimeler: Mobil Robot, Endüstri 4.0, Akıllı Fabrika, Tekstil İmalatı, Çoklu Görev, Yol Planlama, Ontoloji, Bulut Bilişim, Algoritma, Konu Modelleme, Veri Analizi

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INDEX OF ABBREVIATIONS AND ICONS

i40 : Industry 4.0
IoT : Internet of Things
QR : Quick Response
RFID : Radio Frequency Identification
SPARQL : SPARQL Protocol and RDF Query Language
RDF : Resource Description Framework
OMRi40 : Ontology Based Mobile Robot System for Industry 4.0
ARTag : Augmented Reality Tags
YOLO : You Look Only Once
OWL : Web Ontology Language
DL : Description Logic
SKB : Semantic-Knowledge Based
MLN : Markov Logic Networks
XML : eXtensible Markup Language
SW : Semantic Web
T-Box : Terminological Components
A-Box : Assertional Components
W3C : World Wide Web Consortium
SQL : Structured Query Language
RGOM : Reference Generalized Ontological Model
RAMI 4.0 : Reference Architecture Model for Industry 4.0
AMR : Autonomous Mobile Robot
RoboSemProc: Robot Semantic Protocol
SRDL : Semantic Robot Description Language
LDA : Latent Dirichlet Allocation
MALLET : Machine Learning for Language Toolkit
RQ : Research Question
R&D : Research&Development
IDE : Integrated Development Environment
NLTK : Natural Language Toolkit
CCS : Cloud Computing Services
RQ : HyperText Markup Language

R&D : JavaScript
IDE : Cascading Style Sheets
NLTK : Hypertext Preprocessor
YTYID : Yarn Type Identification
CTID : Company Tag Identification
LTID : Laundry Tag Identification
NoSQL : Not Only SQL
DB : Database
RTDB : Realtime Database
SMOID : Sewing Machine Operator Identification
PLPID : Production Line Point Identification
HTTP : Hypertext Transfer Protocol
TDB : TDB is used for RDF storage and query in Jena
MPP : Multi-task Path Planning
TP : Task Priority
SDV : Shortest Distance Value
MS : Microsoft
NULL : A special marker and keyword in SQL indicating that something has no value
USB : Universal Serial Bus
UART : Universal Asynchronous Receiver/Transmitter
1D/2D : 1Dimension/2Dimension
SLAM : Simultaneous Localization and Mapping

1. INTRODUCTION

1.1. Motivation and Objective

Mobile robots are at the forefront of studies in the field of robotics. Interest in the field of mobile robots, where theoretical and applied studies are carried out both academically and in the industry, is increasing day by day.

The term Industry 4.0 (i40) (Meindl, Ayala, Mendonça, & Frank, 2021; López-Robles, et al., 2020; Liao, Deschamps, Loures, & Ramos, 2017), which was presented for the first time by the German consortium at the Hannover Fair in 2011 (Meindl, Ayala, Mendonça, & Frank, 2021; López-Robles, et al., 2020; Liao, Deschamps, Loures, & Ramos, 2017), has led to the beginning of a new era in order to produce new generation solutions to the difficulties occurring in the industrial production processes of European countries and to increase their technological level (López-Robles, et al., 2020; Gonzalez, Alves, Viana, Carvalho, & Basilio, 2017). Industry 4.0, also known as the fourth industrial revolution, consists of nine major technology segments, including cloud computing, cyber-physical systems, big data, internet of things, and autonomous robots. With the developing technologies, wireless communication between devices in industrial environments has gained great importance, and thus, information exchange between devices has become faster, making production processes more efficient and smarter (Gonzalez, Alves, Viana, Carvalho, & Basilio, 2017; Andersen, et al., 2017; Wang, Jiang, Meng, Xie, & Ding, 2021; Fellan, Schellenberger, Zimmermann, & Schotten, 2018).

With the development of i40 applications, production processes must have high efficiency and short changeover times in order for textile factories to maintain their competitiveness in national and international markets. The most important criterion of this competition is to maximize efficiency while minimizing time loss. The sewing workshop where the product parts on the production lines are brought together and sewn is one of the most important stages of the workflow process applied in textile production.

One of the most important factors that cause efficiency and time losses in the sewing workshop is delivery of the various product accessories brought to the production line from the warehouse. The inability to supply these accessories (buttons, labels, etc.) from the warehouse on time disrupts the routine work in the sewing workshop section of a textile factory, and considerable time is lost when the operators on the production lines do not receive the sewing materials (needles, thread spools, etc.) quickly when they need them, greatly reducing productivity.

The aim of this thesis is to develop a solution to the large productivity losses in the factory environment with mobile robot technology, which is one of the i40 applications. Thus, in accordance with the usage scenarios, the aim is for the mobile robot to reach the targets accurately and carry out the tasks at the most affordable cost. The Internet of Things (IoT), Cloud Computing and Mobile Robot which are part of i40 applications, with Ontology, are the four main elements that play a role in this study. Thanks to the IoT, the mobile robot can exchange data and communicate with its environment. The mobile robot that can perform multitasking makes it possible to prevent loss of time caused by bringing the materials from the accessory stock to the sewing workshop. The intention is for the mobile robot system to carry out the given tasks in the best way by choosing the most suitable routes using the task priority (priority factor) algorithm created in cloud computing for tasks in the factory environment.

In the present thesis study, an ontology based semantic structure has been developed in the phase of drawing up the motion plan of the mobile robot and performing the current task depending on the decision support system. This is an innovative approach for a multitasking mobile robot system in the textile factory environment. Fulfillment of the multitasks for which the mobile robot is responsible ensures that the operations performed are reported to the cloud computing system via the IoT and that the tasks are completed.

1.2. Methodology

The mobile robot system in this thesis was run in the CoppelaSim simulation environment by communicating with the Python Programming Language and Apache Jena Fuseki Server. The study includes both software and hardware components. QR (Quick Response) code and RFID (Radio Frequency Identification) tag reader devices in the mobile robot provide different usage scenarios. The data processed by the mobile robot was taken from the physical environment by QR code and RFID tag readers and sent to the cloud computing side for analysis. These two sensors were tested and their results were interpreted with comparative analyses such as latency time, processing speed, positioning and routing performances. As a result of these analyses, it was determined which method was more efficient.

In addition, an ontology based semantic structure has been developed for guiding the mobile robot, determining its route and performing the next task. In this way an innovative solution with a mobile robot system that can perform multiple tasks has been developed to amend the efficiency and time losses experienced in the textile factory. The ontology based semantic structure was implemented in the Apache Jena Fuseki Server which is a SPARQL Protocol and RDF Query Language (SPARQL) server. Various queries were made to the data repository in cloud computing, and the results were produced for the decision support system and sent to the SPARQL server. The next step was to query the SPARQL server with the RDF (Resource Description Framework) Query Language in line with the request of the mobile robot. These processes were repeated until completion of the multitasking, thus rectifying the loss of efficiency and time in textile factories.

1.3. Contribution

The outputs of this thesis study are intended to aid the formation and technological development of startup companies by implementing various Research&Development (R&D) projects in the field of mobile robots, creating an important industry-oriented value within the framework of Industry 4.0. The contributions of this thesis in this context are as follows.

1. Topic modeling and bibliometric analyses were carried out to observe the research trends of mobile robots, which have an important place in Industry 4.0 applications. The results of these analyses are included as a part of this thesis and contribute to future studies as a guide.
2. A cloud-based robotic simulation environment is created according to the mobile robot usage scenarios. In addition, a new cloud-based software system is developed to access the robot simulator for path planning and navigation of the mobile robot. This process was carried out successfully by providing tests and controls.
3. It has been ensured that RFID and QR code tags are successfully read by the sensors which are RFID and QR code readers integrated into the mobile robot simulator and communicated with the cloud computing system and ontology. During the multi-tasking of the mobile robot, which target points the mobile robot will go to first have been realized by the task priority algorithm and ontology to be developed. The stability and accuracy parameters of the mobile robot system were tested. It has been ensured that RFID and QR code tags are successfully read by the sensors, i.e. RFID and QR code readers integrated into the mobile robot simulator and in communication with the cloud computing system and ontology. The multitasking of the mobile robot, establishing which target points the mobile robot will go to first was realized by the task priority algorithm and ontology to be developed. The stability and accuracy parameters of the mobile robot system were tested.
4. The software system created with cloud computing and ontology; permits the data produced by the mobile robot and the employees in the factory to be stored instantly.

The data examined during the preprocessing stage come ready for analysis. The prepared data are analyzed in the task priority algorithm. The order of multitasking is kept in the Fuseki Server. In line with the mobile robot's request for the next task, the RDF query is run and the current route information is presented. All these processes have been tested and successfully carried out by cloud computing and ontology.

2. THEORETICAL FOUNDATIONS

In this study, the literature survey was gathered under three main subtitles. The first of these is *Theoretical Foundations of the Mobile Robot within the Scope of Internet of Things and Cloud Computing*, which examines studies in the literature in the field of mobile robots in which both the IoT and cloud computing are used. The second main subtitle is *Theoretical Foundations of the Mobile Robot within the Scope of Ontology*, where the mobile robot and ontology are used together. The third and last main subtitle is *Theoretical Foundations of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution*. In this section, studies of topic modeling and bibliometrics analyses in many areas, especially Industry 4.0, and the tools used while making topic modeling analysis are mentioned.

2.1. Theoretical Foundations of the Mobile Robots within the Scope of Internet of Things and Cloud Computing

The literature summary of this section was published in Proceedings of the Joint Ontology Workshops 2022 within the scope of our study (Öztürk, Uğuz, Özyer, & Coşkunçay, 2022). According to studies in the literature, textile factories should maximize efficiency by minimizing time loss in order to maintain their competitiveness in national and international markets (Kanat & Güner, 2007; Dogan & Takci, 2015). Today, it is possible to prevent efficiency losses in factories with mobile robot, IoT and cloud computing technologies in Industry 4.0 applications.

There are many studies in the literature in which mobile robot, IoT and cloud computing are used together. Analyses are performed by taking data from various sensors such as temperature, humidity and air quality placed on the mobile robot and transmitting them to remote servers in cloud computing. In addition, the mobile robot is moved by positioning and path planning (Meena, Prabha, & Pandian, 2014; Prabha, Antony, Meena, & Pandian, 2014; Kumari, Kumar, & Singhal, 2020; Jain, Saikia, Rai, & Ray, 2020; Durmuş & Güneş, 2019; López-Alfaro, et al., 2020). Various experiments and tests such as positioning and path planning were carried out using the IoT and cloud computing in the fields of mobile robot.

In one study, the robot dynamically and automatically updated its navigation configuration by providing access to the cloud service through certain environmental tags consisting of a number of Augmented Reality Tags (ARTag) and QR code (Limosani, Manzi, Fiorini, Cavallo, & Dario, 2016).

In another study, a mobile robot platform was designed and produced for industrial use. The robot is controlled to move from one location to another using the line tracking mechanism. RFID tags are used to identify user-predetermined locations. The results showed that the prototype could follow the line and reach any pre-registered location from the application via IoT (Kamarudin, 2019).

In yet another study, a mobile robot platform has been created in the field of agriculture. This platform collected data from agricultural areas by using mobile robot and IoT, analyzing and tracking the collected data by sending them to cloud servers (Durmuş & Güneş, 2019).

A further study presents the design of a mobile robot using IoT architecture to be controlled remotely. The machine learning algorithms in this study recognize two classes of objects in landscape images: agave plants and stones. A convolutional neural network is used for object detection known as You Look Only Once (YOLO), which provides 81.2% accuracy in recognizing both classes (López-Alfaro, et al., 2020).

Examination of the literature reveals many studies on the use of IoT and cloud computing in the field of mobile robots in recent years. Most of the studies perform analyses by receiving data from various sensors and transmitting them to the cloud computing side, as well as moving the mobile robot by positioning and path planning (Meena, Prabha, & Pandian, 2014; Prabha, Antony, Meena, & Pandian, 2014; Kumari, Kumar, & Singhal, 2020; Jain, Saikia, Rai, & Ray, 2020; Durmuş & Güneş, 2019; López-Alfaro, et al., 2020). It emerges from these studies that the mobile robot is open to new approaches in terms of system, design and algorithm development according to its usage areas. We may state with confidence that IoT and cloud computing-based mobile robot applications and usage areas will become more widespread with the developing technology in the oncoming years.

2.2. Theoretical Foundations of the Mobile Robots within the Scope of Ontology

The literature summary of this section was presented at 12th International Conference on Industrial Technology and Management (ICITM 2023) within the scope of our study (Uğuz, Özyer, & Coşkunçay, 2023). This section deals with research topics and software tools that have been investigated utilizing ontology techniques for robotics over the last decades. In numerous robotics studies, semantic knowledge representation has been used. Various studies used Web Ontology Language (OWL) or RDF, which provide appropriate resources for the definition of information in a form intelligible for software systems (Radakovič, Vrba, & Obitko, 2010), as the format for the knowledge description. Before examining OWL and RDF, it is useful to review the use of Description Logic (DL). DL can be used to signify the robot's information about its own world in formulated form (Al-Moadhen, Packianather, Setchi, & Qiu, 2014).

One of the key areas of study in the domain of robotics is task planning. The variety and complexity of control parameters in task planning were highlighted by Xia et al. They created ontologies for robot manipulators and used Web OWL and RDF to evaluate the advantages of ontology and semantic web services for the robot control system. According to their research findings, the method of the Semantic Web Service based on Ontologies boosted the system's adaptability. Additionally, it enhanced the knowledge validity and increased the real-time based application of remote robot control systems in industrial settings (Xia, Liu, Song, & Tan, 2007).

Radakovic et al. created an intelligent manufacturing system utilizing ontology languages such as OWL and RDF. Their study covers the most recent application-oriented aspects of agent-based intelligent production control systems that are reusable, durable, and adaptable. They also sought to integrate information description methodologies with the application of ontologies as multi-agent system control in the industrial area (Radakovič, Vrba, & Obitko, 2010).

In another study, Al-Moadhen et al. specified that the Semantic-Knowledge Based (SKB) plan generation for uncertainty in existing of objects. Additionally, they suggested a new approach to build task plans using Markov Logic Networks (MLN) which is based on probabilistic values. They also used the OWL model to apply test scenarios for a mobile robot (Al-Moadhen, Packianather, Setchi, & Qiu, 2014).

RDF and OWL are frequently used languages with knowledge representation structures that can be suitable to specify robot environments via ontologies. In addition, they have eXtensible Markup Language (XML)-based file format to store formal definitions. OWL is a syntactical extension of RDF, a tool for semantically describing knowledge on the Semantic Web (SW) and providing an expressive and reasoning ability of Description Logic in the SW (Radakovič, Vrba, & Obitko, 2010; Al-Moadhen, Packianather, Setchi, & Qiu, 2014; Saeed, Fathi, & Kuhnert, 2018). Knowledge in DL is consisted of two key components. The first of these are known as terminological components (T-Box) which describe ontology and defined the concepts, i.e. information that never changes, and the second known as assertional components (A-Box) which define knowledge base and make note of its instances, i.e. information that may change with respect to their real-world state and is continually updated (Radakovič, Vrba, & Obitko, 2010; Al-Moadhen, Packianather, Setchi, & Qiu, 2014; Saeed, Fathi, & Kuhnert, 2018; Eich & Hartanto, 2014). In addition, ontologies simplify the automatic generation of axioms through a process known as reasoning (Yahya, Breslin, & Ali, 2021).

Saeed et al. presented a novel approach for utilizing RDF in the robotics field (Saeed, Fathi, & Kuhnert, 2018). RDF is one of the essential tools for creating machine-readable data representations on the semantic web, as advised by the World Wide Web Consortium (W3C). An obligatory characteristic of this form is that it includes a subject, a predicate, and an object. XML is the language which has been used to describe RDF, which is an easy to figure out and human legible form (Yilmaz, Yazici, & Cinar, 2021; Saeed, Weber, Fathi, & Kuhnert, 2019; Mohammed Saeed, Fathi Kazerouni, Fathi, & Kuhnert, 2020). As part of Saeed et al.'s approach they simulated a mobile robot and its surrounding environment, as well as a camera sensor to assist the robot in navigating. Additionally, they used the SPARQL to retrieve data from pertinent sources. The SPARQL protocol is proposed to be used with RDF, and is similar to the Structured Query Language (SQL) structure. SPARQL is a well-known query language and a protocol for collecting data (Mohammed Saeed, Fathi Kazerouni, Fathi, & Kuhnert, 2020). A SPARQL query, which allows users to search for specific data in RDF, provides path finding and navigation for robots.

Eich et. al have two scout robots and a mobile manipulator for space scenario. They proposed an approach using spatial features and fuzzy logic-based reasoning to specify objects and transfer the objects to a base station with ontology. In addition, their study describes T-Box and A-Box (Eich & Hartanto, 2014). Yahya et. al. also described T-Box and A-Box in their study. These are very important for intelligent manufacturing such as controlling knowledge related to resource optimization, equipment maintenance, and various types of production and services which are on-demand. They investigated the usage of the Semantic Web and Knowledge Graphs for Industry 4.0 and recommended an improved Reference Generalized Ontological Model (RGOM) based on the Reference Architecture Model for Industry 4.0 (RAMI 4.0). Their aim is to highlight major problems and opportunities that could originate from the association of these existing technologies for Industry 4.0 (Yahya, Breslin, & Ali, 2021).

Like Yahya et. al (Yahya, Breslin, & Ali, 2021), Yılmaz et. al also conducted a study in the Industry 4.0 domain. They composed a semantic ontology using RDF to monitor different types of representative faults such as environmental, mechanical, and software errors in an Autonomous Mobile Robot (AMR). AMR is one of the major components for the progress of the smart manufacturing field, and their usage in Industry 4.0 improves regularly. The Ontology API serves as the base for the knowledge layer in their study and they used SPARQL for querying the machine that supplies the order conditions. The ontology model is established with Jena Fuseki Server which is SPARQL endpoint server. A SPARQL query that runs the ordering criteria is realized on the basis of the ontology. Consequently, they stated the importance of RDF for Industry 4.0 (Yilmaz, Yazici, & Cinar, 2021).

Saeed et al. used RDF to describe navigation of a mobile robot semantically in an ontology. They suggested a recent and fruitful way of expressing semantic relationships within the navigation ontology by using RDF helper nodes in real-time (Saeed, Weber, Fathi, & Kuhnert, 2019).

In another study, Saeed et al. suggested a system called Robot Semantic Protocol (RoboSemProc). RoboSemProc has ensured the application of semantic technology from scratch for the handling of semantic knowledge generation, real-time ontology population and natural language communication within human-robot interaction. They used the Semantic Web Technology components OWL, RDF, SPARQL and Jena in their study (Mohammed Saeed, Fathi Kazerouni, Fathi, & Kuhnert, 2020).

Wan et al. proposed an ontology-based resource reconfiguration method for resource usage. They utilized OWL, RDF, SPARQL and Jena components for their smart device ontology which describes the smart manufacturing resource, and composed a smart manufacturing resource integration architecture based on their ontology. Subsequently, they investigated the reconfiguration of the intelligent manipulator as an practice case based on the ontology, and they confirmed its applicability in smart manufacturing. As a result, their study is now maintained as a recent technique for the reconfiguration of production resources (Wan, et al., 2018).

Ji et al. built a semantic knowledge ontology for representing two primary types of knowledge, environmental description and robot primitive actions. Their method combined the representation of semantic knowledge with classical approaches in Artificial Intelligence (AI) to build an elastic framework which can help service robots in respect of task planning (Ji, et al., 2012).

Li et al. proposed to help robots to handle objects with semantic constraints such as grasp location, grasp type, trajectory limitation that are learnt from human manipulation behaviors. They proposed a representation of human manipulation behaviors in machine comprehensible semantics and a collaborative reasoning concept and stated that the robot manipulation can be completed with consciousness and in an appropriate manner for the object and task (Li & Tian, 2020).

Kunze et al. presented Semantic Robot Description Language (SRDL) and deduction mechanisms for defining robot components, capabilities and actions. SRDL utilizes OWL for modeling knowledge and authorizes illations in respect of the ability of robots to carry out specific actions (Kunze, Roehm, & Beetz, 2011).

Bouguerra et al. defined a recent smart execution monitoring approach for mobile robots using semantic knowledge in indoor environments. The primary idea is to compute prospects side by semantic domain knowledge, that can be accurately tracked at application time by the robot. Thus, they offered a representation of the semantic information that is used to monitor execution for a real mobile robot (Bouguerra, Karlsson, & Saffiotti, 2007).

2.3.Theoretical Foundations of the Topic Modeling Analysis for Mobile Robots within the Periods before and after the Industry 4.0 Revolution

Coniderable academic research has been conducted to date regarding Industry 4.0, as have several bibliometric analyses utilizing the Scopus database to examine the effectiveness and conceptual growth of publications generated within the context of i40 and to provide insights and views for future research (López-Robles, et al., 2020; Kipper, Furstenau, Hoppe, Frozza, & Iepsen, 2020). In addition, it was noted in one of the publications that every year, the number of studies on the subject of i40 doubles (Kipper, Furstenau, Hoppe, Frozza, & Iepsen, 2020).

With respect to bibliometrics, there have been numerous studies done in the area of topic modeling. By undertaking data exploration in texts in a particular field, topic modeling is a powerful text mining technique that produces highly relevant coding categories among text documents (Mohr & Bogdanov, 2013; Ala & Uğuz, 2021; Jelodar, et al., 2019). Overview of the studies in the literature indicates that the Latent Dirichlet Allocation (LDA) model, which offers efficient results in the field of topic modeling, is extremely popular (Jelodar, et al., 2019). It is used in various fields including software engineering (Tokdemir, 2021), health (Paul & Dredze, 2014), culture (DiMaggio, Nag, & Blei, 2013), communication (Maier, et al., 2018), social media (Zhao, et al., 2011) and regional development (Ala & Uğuz, 2021). Additionally, several studies (Ala & Uğuz, 2021; Tokdemir, 2021) have reported better results using MALLET (A Machine Learning for Language Toolkit) (McCallum, 2002), a software package based on the Java programming language, along with LDA.

3. MATERIAL AND METHOD

In this study, the Material and Method part was collected under two main subtitles. The first of these is *Material and Method of Ontology Based Mobile Robot System for Industry 4.0 (OMRi40)*, where the IoT, Cloud Computing, Mobile Robot, and Ontology are used together. The second main subtitle is *Material and Method of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution*. This section gives details of the research methods and tools of the topic modeling and bibliometrics analyses.

3.1. Material and Method of Ontology Based Mobile Robot System for Industry 4.0 (OMRi40)

In this section, Ontology Based Mobile Robot System for Industry 4.0 (OMRi40) was created for this thesis study. The system is grouped under 3 headings: *Cloud Computing Services for the OMRi40*, *Ontology and Algorithm for the OMRi40*, and *Simulation Environment for the OMRi40*. A general overview of the OMRi40 is shown in Figure 3.1. It consists of three layers: Cloud Computing Services Layer, Ontology and Algorithm Layer, and Simulation Environment Layer.

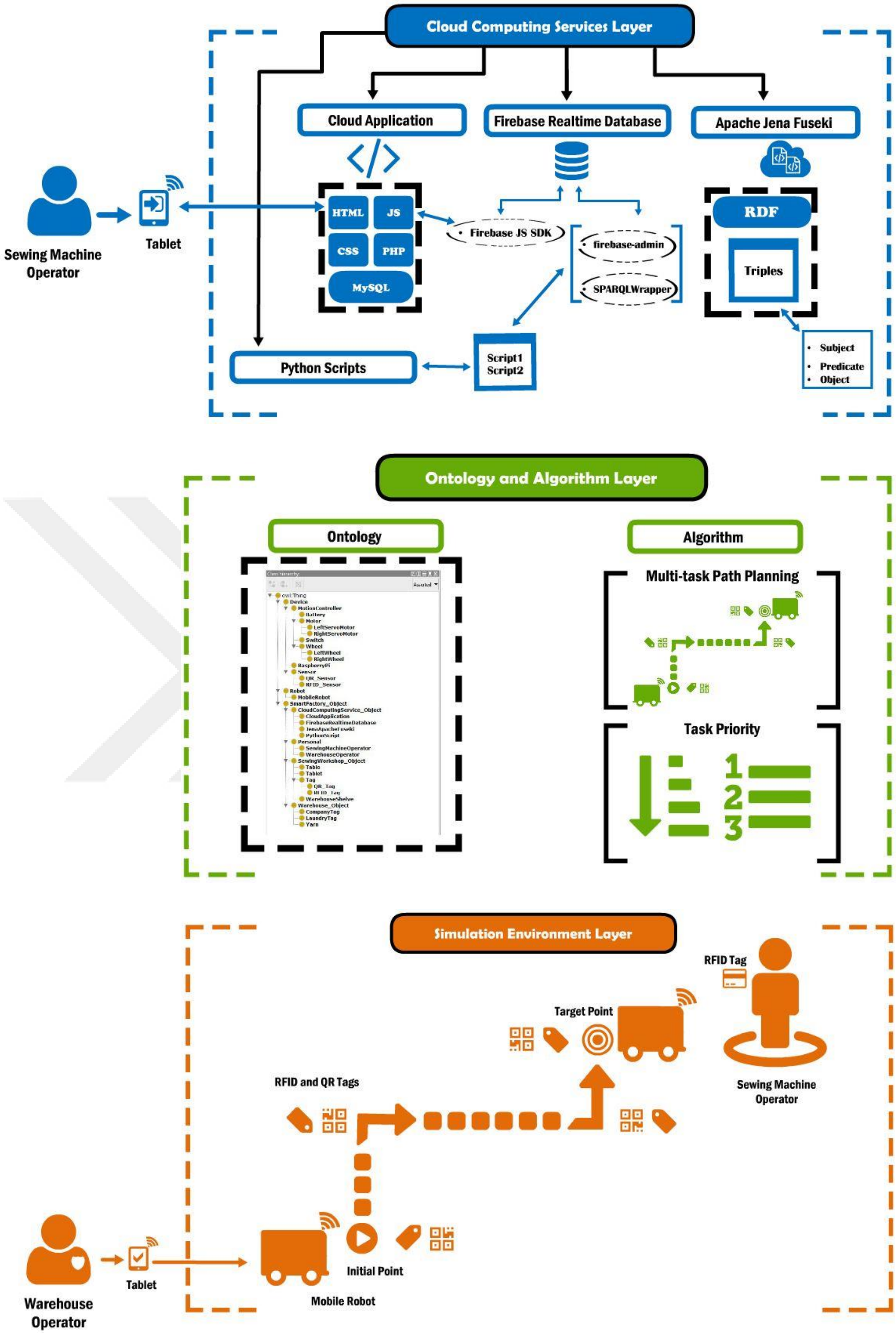


Figure 3.1. A General Overview of the OMRi40

3.1.1. Cloud Computing Services for the OMRi40

In this part, the Cloud Computing Services (CCS) were collected under four subheadings, and the CCS Layer of the OMRi40 is shown in Figure 3.2. The first of these is Cloud Application for the OMRi40, which has a user interface for requests for materials by sewing machine operators. The second subheading is Realtime Database for OMRi40, where cloud application data are stored**.** The third of these is Apache Jena Fuseki for OMRi40, which stores RDF triples of the tasks for querying the current task of the mobile robot. The fourth and last subheading is Python Scripts for OMRi40, which communicates both Realtime Database and Apache Jena Fuseki.

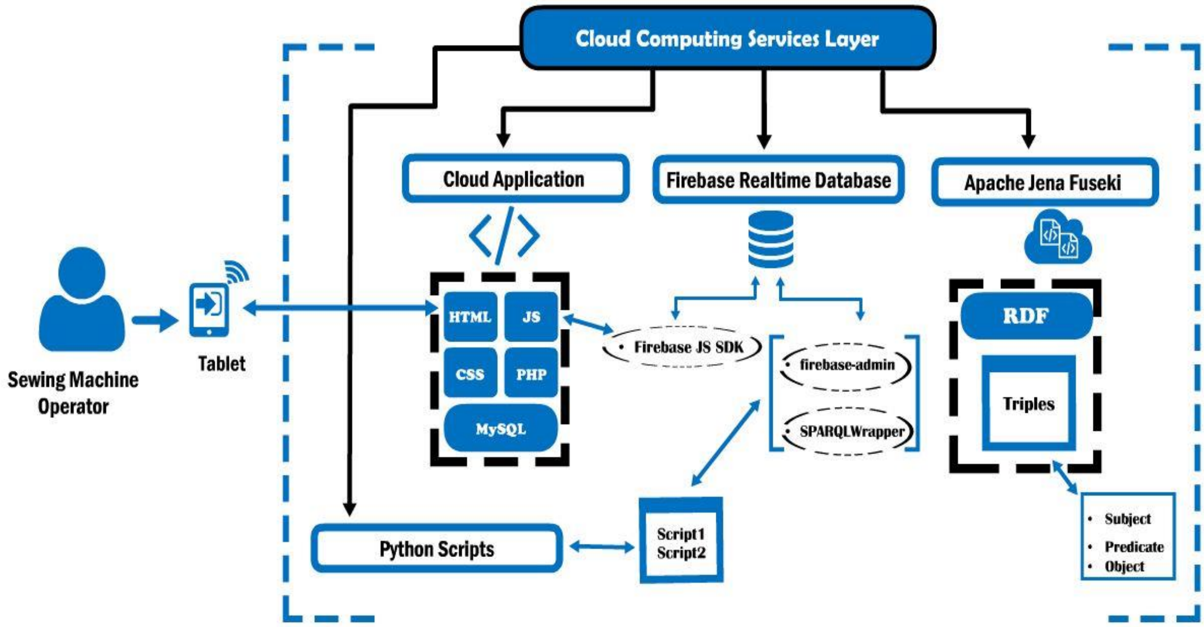


Figure 3.2. Cloud Computing Services Layer of the OMRi40

3.1.1.1. Cloud Application for the OMRi40

In this section, the material requirements of the employees in the textile workshop were recorded through cloud application. The cloud application consists of HTML (HyperText Markup Language), JS (JavaScript), CSS (Cascading Style Sheets), PHP (Hypertext Preprocessor) and MySQL components. Access to this cloud application is provided via tablets that are available in production lines of the textile workshop. *Material Type, Material Type Detail* and *Quantity* information were received from the user as request information. In addition to these, *Timestamp, Is Analyzed, Material Priority Value, Personal ID, Production Line Point* data were created on the backend of the cloud application and recorded in the Realtime Database for some analyses in the OMRi40 system.

The name of the materials requested by the user is shown in the *Material Name* column of Table 1, where detailed information on the materials prepared as a sample can be found in the *Material Type Detail (Sample)* column.

Table 1. Description of the Sample Materials by Category Name

Material Name	Material Type Detail (Sample)
Yarn Type	YTYID_AX_001 YTYID_DX_001 YTYID_CY_002 YTYID_TZ_003 YTYID_WZ_005 YTYID_LY_007 YTYID_YY_007
Company Tag	CTID_A_002 CTID_B_001 CTID_C_003
Laundry Tag	LTID_X_005 LTID_X_003 LTID_Y_002 LTID_Z_001 LTID_Z_007

In the Material Type Detail (Sample) column, the abbreviations YTYID, CTID and LTID represent Yarn Type Identification, Company Tag Identification and Laundry Tag Identification, respectively, followed by the underscore "_" symbol, and a unique alphanumerical code to facilitate requesting product materials and ascertaining the stock status. Moreover, Figure 3.3 provides a more detailed explanation of the abbreviations in Table 1. Thus, it is a simple matter to request product materials and to examine the stock status.

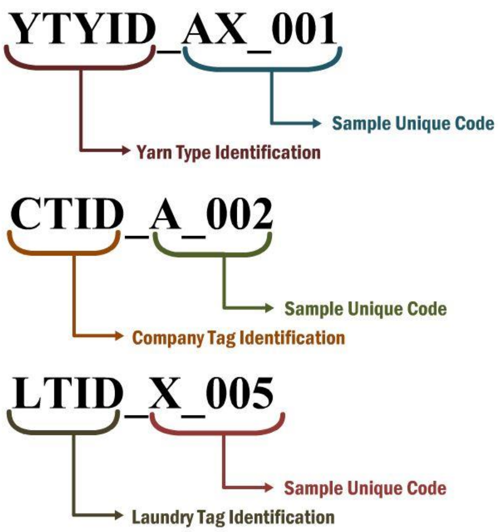


Figure 3.3. Explanation of Abbreviations - I

The data in each column of Table 1 are used in the Cloud Application for OMRi40 framework and shown in Figures 3.4, 3.5 and 3.6. A sample request by the sewing machine operator is shown in Figure 3.7.

Figure 3.4. Cloud Application (Request Material Platform) for the OMRi40 – I

Figure 3.4 shows the state before data entry is made in the Cloud Application.

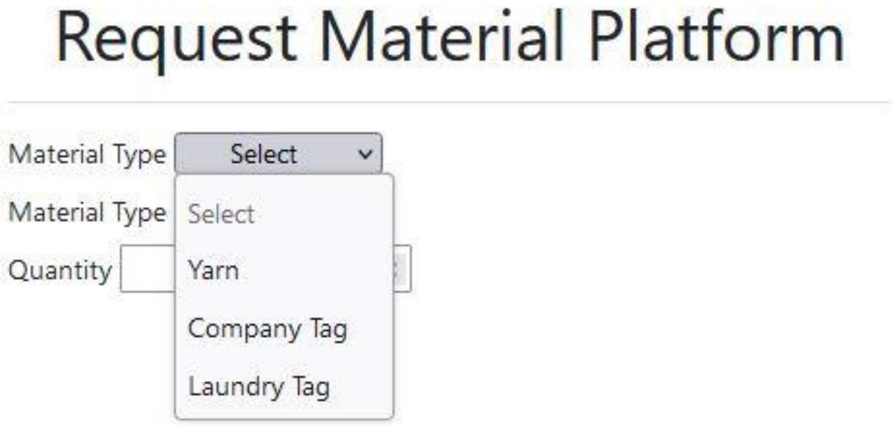


Figure 3.5. Cloud Application (Request Material Platform) for the OMRi40 – II

Figure 3.5 shows selection of the Material Type variable in the Cloud Application.

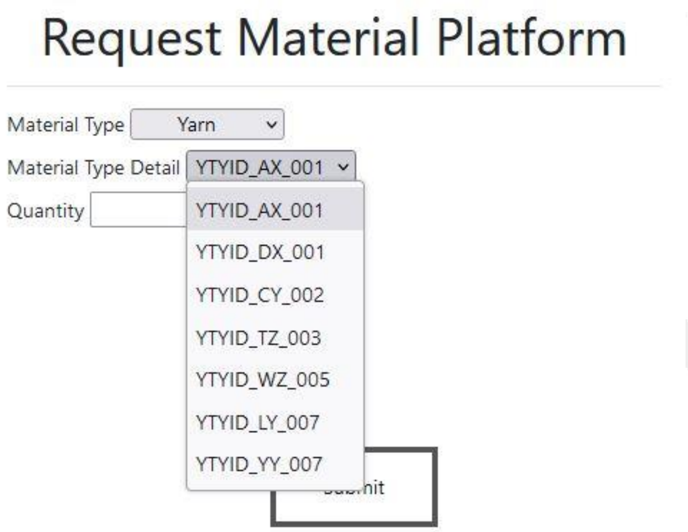


Figure 3.6. Cloud Application (Request Material Platform) for the OMRi40 – III

Figure 3.6 shows selection of the Material Type Detail variable in the Cloud Application.

Figure 3.7. Cloud Application (Request Material Platform) for the OMRi40 – IV

Figure 3.7 shows a data entry of the Quantity variable in the Cloud Application. Clicking on the Submit button in Figure 3.7 sends these data directly to the Realtime Database and instantly recorded successfully.

3.1.1.2. Realtime Database for OMRi40

In today's technology, various cloud applications of the industry factories or companies are using the "Not Only SQL" (NoSQL) database, very interesting and popular because NoSQL data storage can be transferred to the cloud and can support fast data access (Sachdeva & Gupta, 2019).

The use case scenario of this thesis includes a smart textile factory that produces big data with Industry 4.0 competencies. So, NoSQL DB is a very useful database for this study with its instant data transfer to the cloud feature, data reading and writing operation in the cloud and nested data structure.

In this study, Firebase Realtime Database (RTDB) was used and a database was created for the OMRi40 in the name of OMRi40_RTDB. Figure 3.8 shows the Nested Data Structure for the RTDB of the OMRi40.

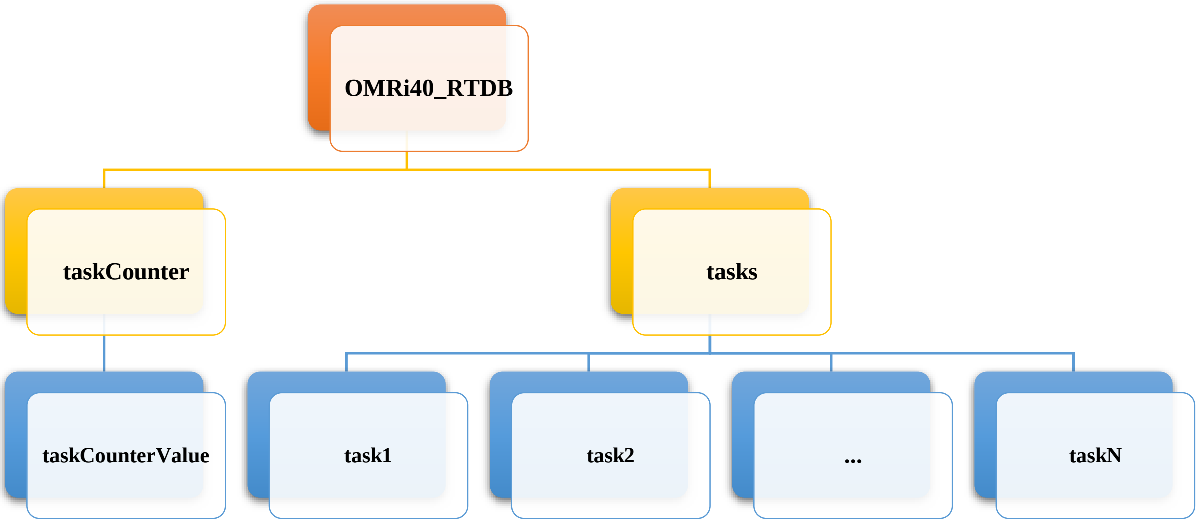


Figure 3.8. Nested Data Structure for the RTDB of the OMRi40

The data collected by the sewing machine operator's data entry are recorded with NoSQL data structure. Figure 3.9 contains two main parts under OMRi40_RTDB: taskCounter and tasks.

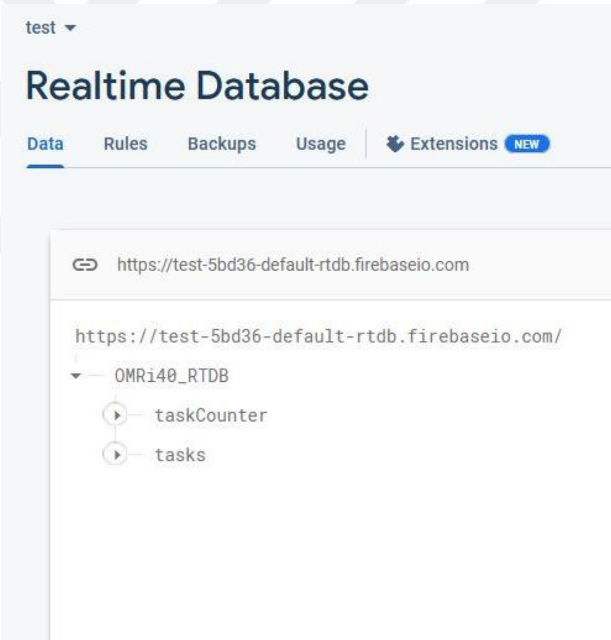


Figure 3.9. Realtime Database for OMRi40 – I

In Figure 3.10, task numbers and task information are located under the *tasks* section, within which the variable *taskCounterValue* below *taskCounter* records the total number of tasks.

Figure 3.10. Realtime Database for OMRi40 - II

When a new task is added on the cloud application side, this taskCounterValue information is obtained and the updated value is saved by adding +1 to the taskCounterValue variable.

Table 2. Description of the Realtime Database for OMRi40

Variable Name	Data Type	Data Sample
timestamp	DateTime	17/11/2022 10:07:24.94164
isAnalyzed	Boolean	0
materialPriorityValue	Integer	1
materialType	String	Yarn
materialTypeDetail	String	YTYID_AX_001
personalID	String	SMOID_212
quantity	Integer	3
productionLinePoint	String	PLPID_B2_5

The abbreviations SMOID and PLPID in Table 2 represent Sewing Machine Operator Identification and Production Line Point Identification respectively, followed by the underscore "_" symbol. In addition, Figure 3.11 contains a more detailed explanation of these abbreviations.

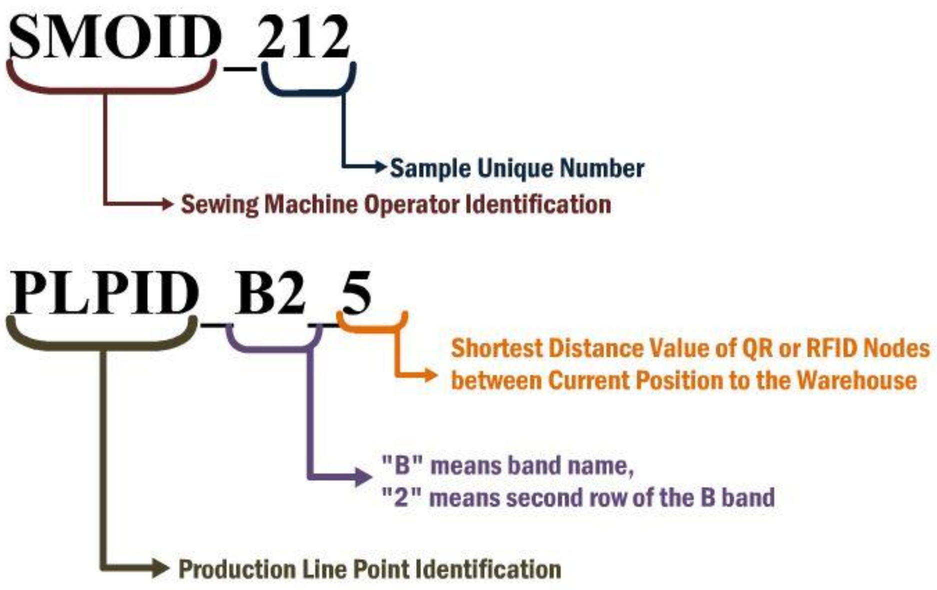


Figure 3.11. Explanation of Abbreviations - II

In Figure 3.12, the material request made by an employee (e.g. SMOID_212) in the textile workshop is recorded as task1. Along with the data variables appearing in the sample material request in Figure 9, the important data parameters in Table 2 have been added to the Firebase Realtime Database via the cloud application.

Figure 3.12. Realtime Database for OMRi40 – III

These data were used by the Fuseki Server after being analyzed with the Python application developed in cloud computing services.

3.1.1.3. Apache Jena Fuseki for OMRi40

Apache Jena Fuseki, a SPARQL server, enables various SPARQL queries over HTTP to access RDF data. Fuseki is tightly integrated with TDB, a component of Jena, which has a triple store structure for storing and querying RDF data. It has been stated that TDB can be used as a high-performance RDF store on a single machine.

We visited *https://jena.apache.org/download* to install the latest released version of Apache Jena Fuseki, version 4.7.0. The downloaded *apache-jena-fuseki-4.7.0.zip* file was extracted and moved to the C directory. Then, Command Prompt is opened as in Figure 3.13 to run the Fuseki Server. On the command line *cd C:\apache-jena-fuseki-4.7.0* and then *fuseki-server --update --mem /ds* was run.

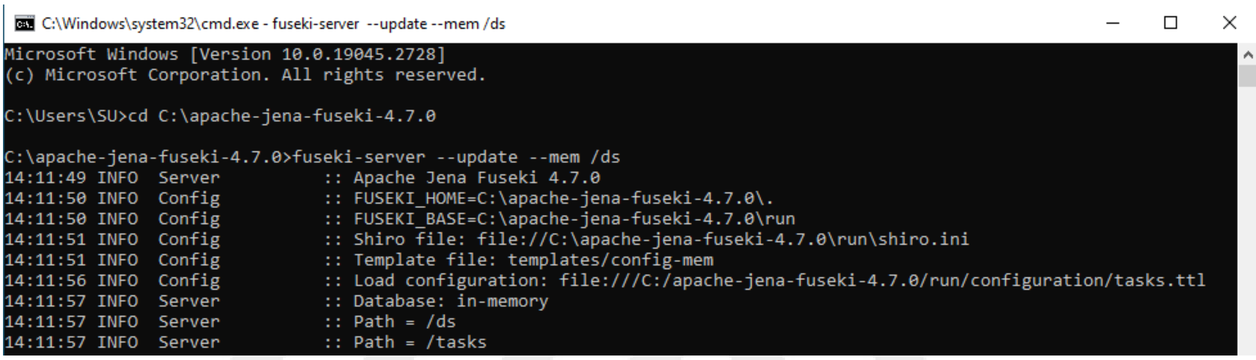


Figure 3.13. Fuseki Server Running on MS Command Prompt

After running the commands in Figure 3.13, the Fuseki Server starts running locally at *http://localhost:3030/#/*.

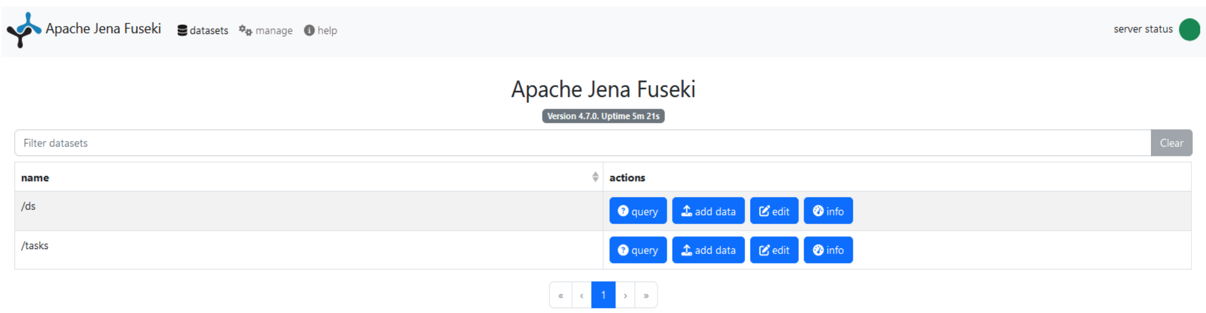


Figure 3.14. Apache Jena Fuseki - Homepage

The Fuseki Server includes *ds* dataset as the default dataset as shown in Figure 3.14. A dataset was created with the name *tasks* for the OMRi40 system. Clicking on the query in the actions section on the right brings up various queries for the triples in the tasks dataset. The SPARQL Query field and default query text are shown in Figure 3.15.

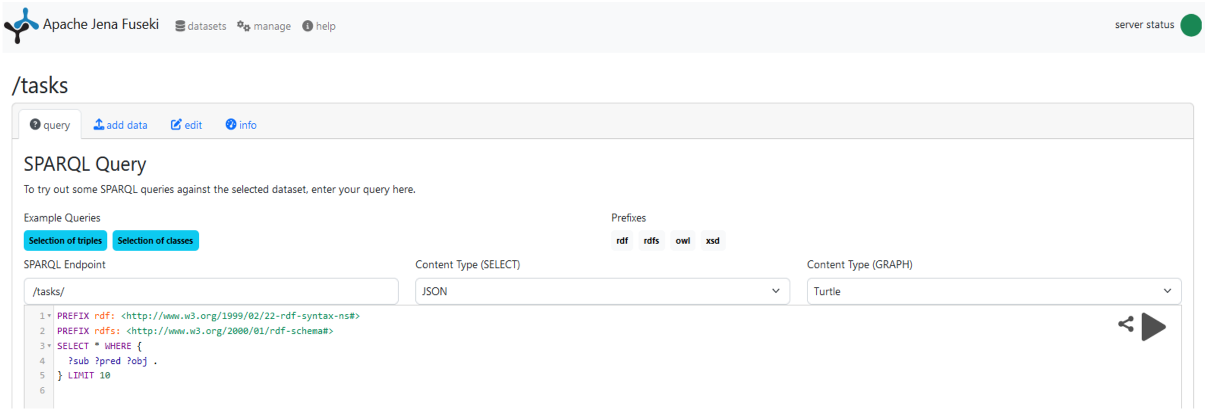


Figure 3.15. Apache Jena Fuseki - SPARQL Default Query Text

A Python wrapper called SPARQLWrapper is used to execute queries remotely on the OMRi40 system. Thus, SPARQLWrapper helps to create the query call through the Python programming language and transform the result into a more manageable format for different purposes. In addition, the data on the Realtime Database side via Python are first passed through the data preprocessing part, then the task priority algorithm is applied and saved on the Fuseki Server side. The mobile robot is then enabled to query the current task from the Fuseki Server via Python according to the priority value and to perform that task.

3.1.1.4. Python Script for the OMRi40

Scripts written in the Python programming language have an important place in the OMRi40 framework. Python provides data exchange by both Firebase Realtime Database and Apache Fuseki Server using its libraries which are: firebase_admin and SPARQLWrapper. It also performs the analysis of these data and transmits the tasks to the mobile robot in order. A sample of retrieving data in the Python using the firebase_admin library is shown in Figure 3.16.

```python
import firebase_admin
from firebase_admin import credentials
from firebase_admin import db


if not firebase_admin._apps:

    cred = credentials.Certificate('serviceAccountKey.json')
    default_app = firebase_admin.initialize_app(cred, {
        'databaseURL': 'https://test-5bd36-default-rtdb.firebaseio.com',
        'databaseAuthVariableOverride': {
            'uid': 'my-service-worker'
        }
    })

ref = db.reference('/OMRi40_RTDB/tasks')
snapshot = ref.order_by_child('isAnalyzed').equal_to(0).get()
for key in snapshot:
    print(key)

for key, value in snapshot.items():
    if(value["isAnalyzed"] == 1):
        ref.child(key).update({"isAnalyzed": 1})
```

Figure 3.16. A Sample of Retrieving Data from the Firebase Realtime Database in Python

An example of inserting data with a SPARQL query in Python using SPARQLWrapper is shown in Figure 3.16.

```
from SPARQLWrapper import SPARQLWrapper, JSON

sparql = SPARQLWrapper("http://localhost:3030/tasks")


sparql.setQuery("""
PREFIX d: <http://localhost:3030/tasks/data#>
PREFIX det: <http://localhost:3030/tasks/details#>

INSERT DATA{
d:task det:productionLinePoint "PLPID_A3_5" ;
det:priorityWeight 6 .

}
""")

sparql.setReturnFormat(JSON)
results = sparql.query().convert()
```

Figure 3.17. A Sample of Inserting Data to the Apache Jena Fuseki using SPARQL Query

In addition, a sample of filtering data with a SPARQL query in the Python using SPARQLWrapper is shown in Figure 3.17.

```
import pandas as pd
from SPARQLWrapper import SPARQLWrapper, JSON

sparql = SPARQLWrapper("http://localhost:3030/tasks")

sparql.setQuery("""
    PREFIX d: <http://localhost:3030/tasks/data#>
    PREFIX det: <http://localhost:3030/tasks/details#>

    SELECT ?productionLinePoint ?priorityWeight
    WHERE
    {
    ?task det:productionLinePoint ?productionLinePoint ;
    det:priorityWeight ?priorityWeight .
    }
    ORDER BY ASC(?priorityWeight)
    LIMIT 1
""")


sparql.setReturnFormat(JSON)
results = sparql.query().convert()

results_df = pd.json_normalize(results['results']['bindings'])
print(results_df[['productionLinePoint.value', 'priorityWeight.value']])
```

Figure 3.18. A Sample of Filtering Data in Apache Jena Fuseki using SPARQL Query

3.1.2. Ontology and Algorithm for the OMRi40

This section describes the Ontology and Algorithm part developed for the OMRi40 system. Figure 3.19 shows the Ontology and Algorithm Layer of the OMRi40. In the Ontology part, an

OWL model was created. In the Algorithm part, Multi-task Path Planning (MPP) and Task Priority (TP) algorithms were developed.

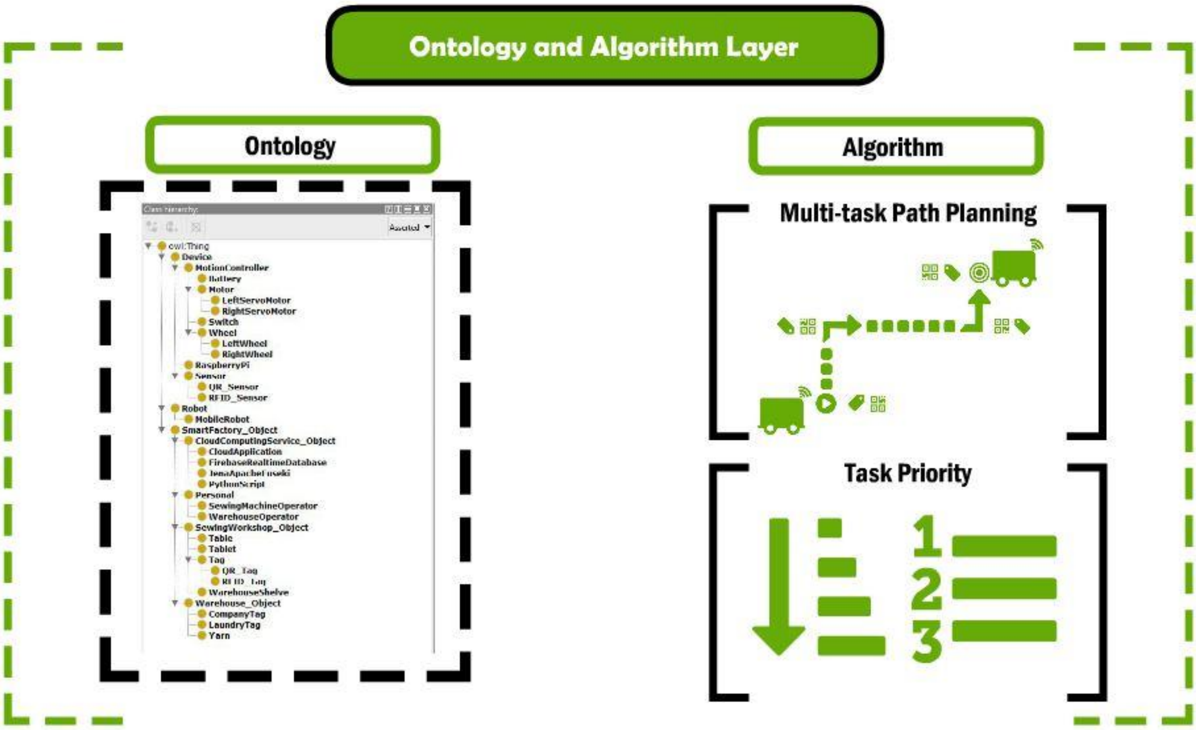


Figure 3.19. Ontology and Algorithm Layer of the OMRi40

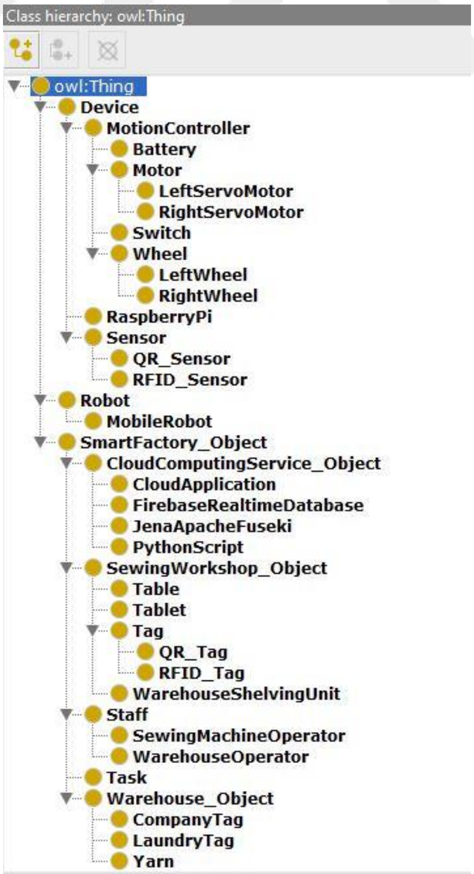


Figure 3.20. Classification Tree of Ontology Concepts for the OMRi40

The Classification Tree of Ontology Concepts for the OMRi40 is shown in Figure 3.20, while the conceptual diagram of the OMRi40 Ontology is shown in Figure 3.21 in detail. Five different papers were used to create the ontology structure in Figures 3.20 and 3.21. The *Device* part of the mobile robot was in Figure 3.21 inspired by the study of Poza-Lujan et al (Poza, Posadas, & Simó, 2009). *SmartFactory_Object* and its subcomponents, *CloudComputingService_Object* and its subcomponents, *SewingWorkshop_Object* and its subcomponents, *Warehouse_Object* and its subcomponents were in Figure 3.21 inspired by the studies of Wan et al., Al-Moadhen et al. and Öztürk et al. (Wan, et al., 2018; Al-Moadhen, Packianather, Setchi, & Qiu, 2014; Öztürk, Uğuz, Özyer, & Coşkunçay, 2022). In Figure 3.21, *MotionController* part of the *Device* was inspired by study of Zeshan et al (Zeshan, Mohamad, Ahmad, & Hussain, 2014).

The Warehouse Object requested by the Sewing Machine Operator in Figure 3.21 is managed by the Warehouse Operator. Requesting and managing the warehouse object is done using the Cloud Application running by the Tablet. Data created by cloud application are sent to Firebase Realtime Database. After the data have been read by a Python Script, they are analyzed with the algorithms developed, and the new data obtained by the analyses are written to Apache Jena Fuseki. Warehouse object requested by the sewing machine operator is displayed by warehouse operator. The warehouse operator puts the requested materials into the material case of the mobile robot, and then activates the mobile robot to start the multi-tasks.

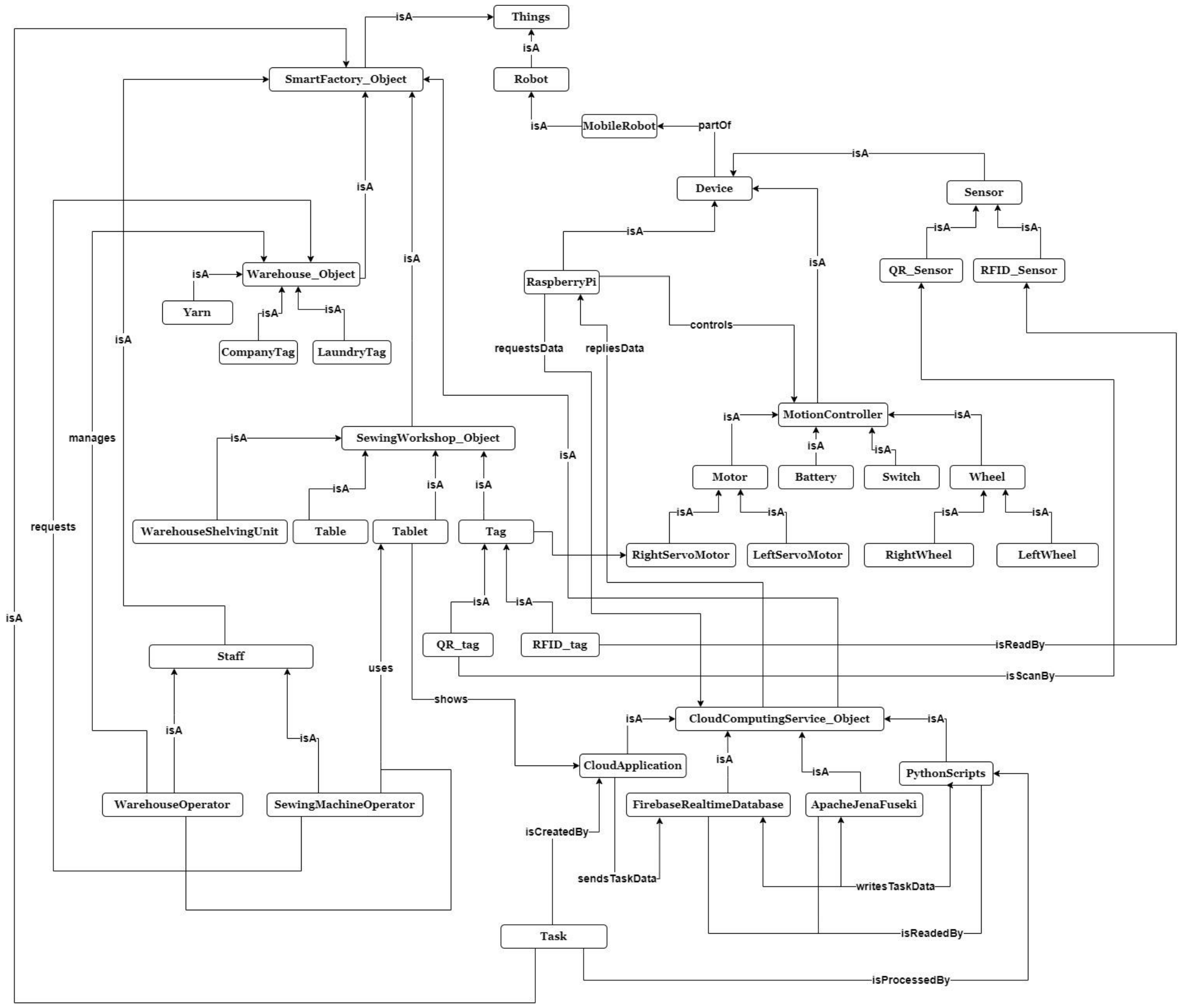


Figure 3.21. Conceptual Diagram of the OMRi40 Ontology

Two algorithms have been developed for the OMRi40. During the creation process of these two algorithms of the OMRi40 framework, the algorithms of the studies of Wan et al. and Muhayyuddin et al. were examined (Wan, et al., 2018; Muhayyuddin & Rosell, 2018). Algorithm 1 is developed for multi-task path planning of the mobile robot.

Algorithm 1. Multi-task Path Planning (MPP) Algorithm of the OMRi40.

Input: MPP()

Output: resultMPP

WorkspaceInit();

terminateMPP = False;

While terminateMPP == False **do**

    FindTagPoint();

    $\boldsymbol{p}_{curr}$ = ReadCurrentTagPoint();

    $\boldsymbol{p}_{target}$ = GetTargetTaskPoint();

    if $\boldsymbol{p}_{\mathrm{curr}} == \boldsymbol{p}_{\mathrm{target}}$ **then**

        DeliverMaterial();

    else if $\boldsymbol{p}_{\mathrm{curr}} \mathrel{!=} \boldsymbol{p}_{\mathrm{target}}$ **then**

```
            continue
      else if p_target == NULL then
            resultMPP = GoToWarehousePoint();
            terminateMPP = True;
      end if
end While
return resultMPP
```

The Mobile Robot runs the *FindTagPoint* function in Algorithm 1 to find the nearest tag point. After the tag point is found, the *ReadCurrentTagPoint* function is run and the current tag point ($\boldsymbol{p}_{\mathrm{curr}}$) information is obtained through the sensor. Then, the *GetTargetTaskPoint* function is run and a SPARQL query is made to the tasks pool on the Apache Jena Fuseki side with a Python script. This tasks pool was created by Algorithm 2. As a result of the SPARQL query made with a Python script, the current target task ($\boldsymbol{p}_{\mathrm{target}}$) information to be carried out at the moment is obtained. If the tag point where the mobile robot is at the moment is the same as current task point, the robot delivers the material, otherwise the *FindTagPoint* function is run again and the process continues until it finds the current task point. Once the relevant current task point has been found, the *DeliverMaterial* function is run and the information that the task has been delivered is written in Apache Jena Fuseki. The mobile robot waits for the RFID tag which acts as a digital signature of the sewing machine operator to be read to start the next task. Thus, the sewing machine operator accepts that it has received the material. When the value from *GetTargetTaskPoint* is NULL, it means there are no tasks left. Then *GoToWarehousePoint* function is executed and the mobile robot returns to the initial point where it was operated by the warehouse operator. In this way the multitasking process is completed successfully and efficiently.

Algorithm 2. Task Priority (TP) Algorithm.

```
Input: TP()
Output: resultTP
WorkspaceInit();
taskList = GetTaskList(notAnalyzed);
if taskList == NULL then
      resultTP = 0;
      break;
else
      for each task in taskList do
            task.timestampRanked = ApplyRank(task.timestamp);
            p = task.timestampRanked;
```

```
        q = task.materialPriorityValue;
        r = task.productionLinePointSDV;
        task.priorityWeight = CalculateTaskPriorityWeight(p, q, r); //priorityWeight(cost)=p*v1+q*v2+r*v3
        WriteProcessedDataToFusekiServer(task.taskID, task.productionLinePoint,
        task.priorityWeight, task.notAnalyzed);
    end for
    resultTP = 1;
end if
return resultTP
```

Algorithm 2 is the task priority algorithm used to determine this multi-task path planning. The data that have not been analyzed in Firebase Realtime Database via Python script by running the GetTaskList function are included in the taskList variable. With the ApplyRank function, the Timestamp information in the taskList is sorted and sent to the timestampRanked variable. This variable is made available for use in the CalculateTaskPriorityWeight function. The variables timestampRanked (p), materialPriorityValue (q), and productionLinePointSDV (r) in the CalculateTaskPriorityWeight function are calculated in Formula 1 and the result is assigned to the priorityWeight variable. SDV represents Shortest Distance Value of the productionLinePoint variable. Then, the WriteProcessedDataToFusekiServer function is run and the values in the taskID, productionLinePoint, priorityWeight, notAnalyzed variables written to Apache Jena Fuseki with a SPARQL query in Python script.

$$priorityWeight(cost) = p * timestampRanked + q * materialPriorityValue + r * productionLinePointSDV \tag{1}$$

In Formula 1: p, q and r are weighted numbers. priorityWeight value gives the cost of the task. the mobile robot performs the tasks in the task pool in the order from minimum to maximum cost. Formula 1 was inspired by study of Xiao-Long et al. (Xiao-Long, Chun-Fu, Guo-Dong, & Qing-Xie, 2017).

3.1.3. Simulation Environment for OMRi40

Figure 3.22 shows the Simulation Environment Layer of the OMRi40 which includes a sample journey of the Mobile Robot from Initial Point to Target Point.

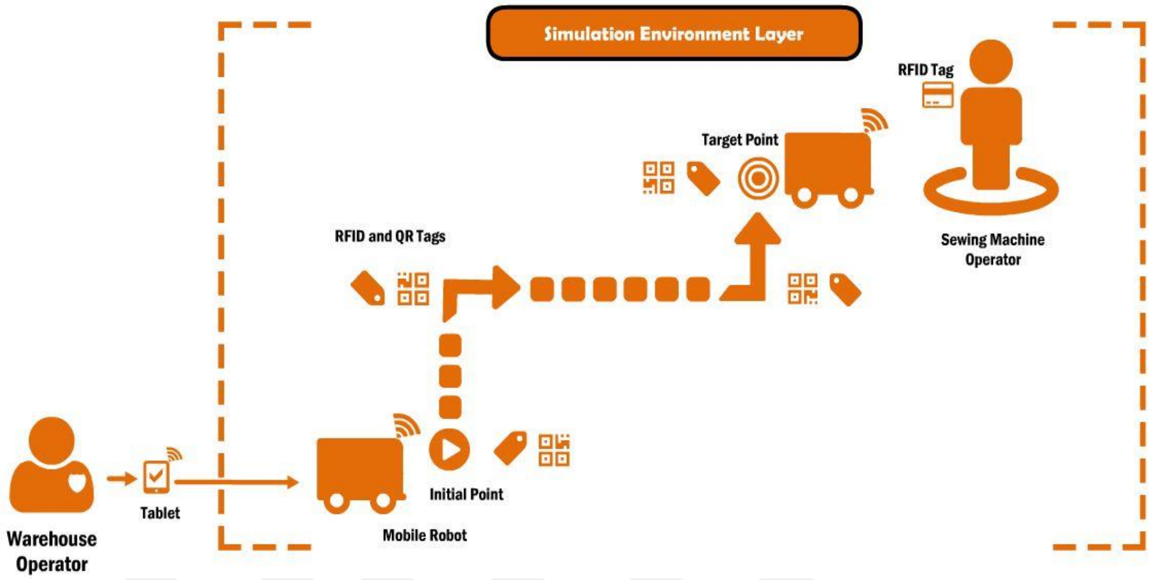
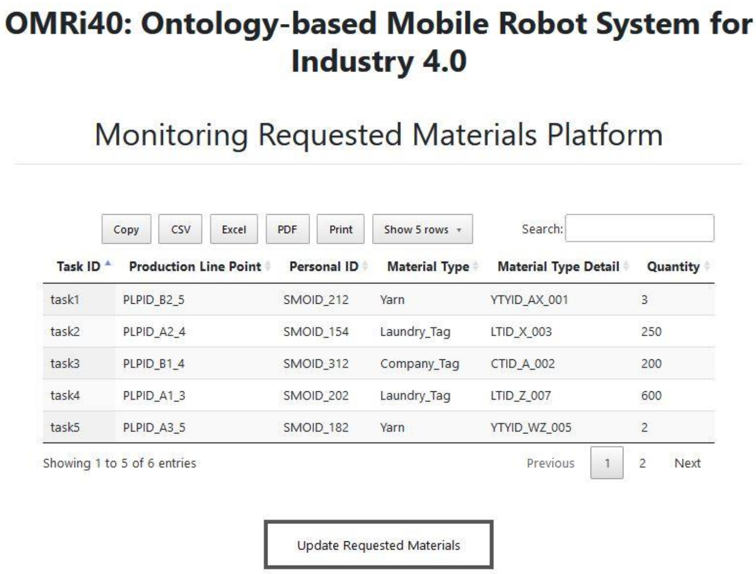


Figure 3.22. Simulation Environment Layer of the OMRi40

Figure 3.23 shows the Cloud Application (Monitoring Requested Material Platform) used by the warehouse operator. The warehouse operator lists the tasks requested by the sewing machine operators, prepares the requested materials, and deposits the materials into the material case of the mobile robot.


OMRi40: Ontology-based Mobile Robot System for Industry 4.0

Monitoring Requested Materials Platform

Copy CSV Excel PDF Print Show 5 rows Search:

Task ID	Production Line Point	Personal ID	Material Type	Material Type Detail	Quantity
task1	PLPID_B2_5	SMOID_212	Yarn	YTYID_AX_001	3
task2	PLPID_A2_4	SMOID_154	Laundry_Tag	LTID_X_003	250
task3	PLPID_B1_4	SMOID_312	Company_Tag	CTID_A_002	200
task4	PLPID_A1_3	SMOID_202	Laundry_Tag	LTID_Z_007	600
task5	PLPID_A3_5	SMOID_182	Yarn	YTYID_WZ_005	2

Showing 1 to 5 of 6 entries Previous 1 2 Next

Update Requested Materials

Figure 3.23. Cloud Application (Monitoring Requested Material Platform) for the OMRi40

The usage scenarios of the OMRi40 system were realized with CoppeliaSim software as seen in Figure 3.24. CoppeliaSim is a robot simulator for fast prototyping and verification in industry, education and research (Coppelia Robotics, 2023).

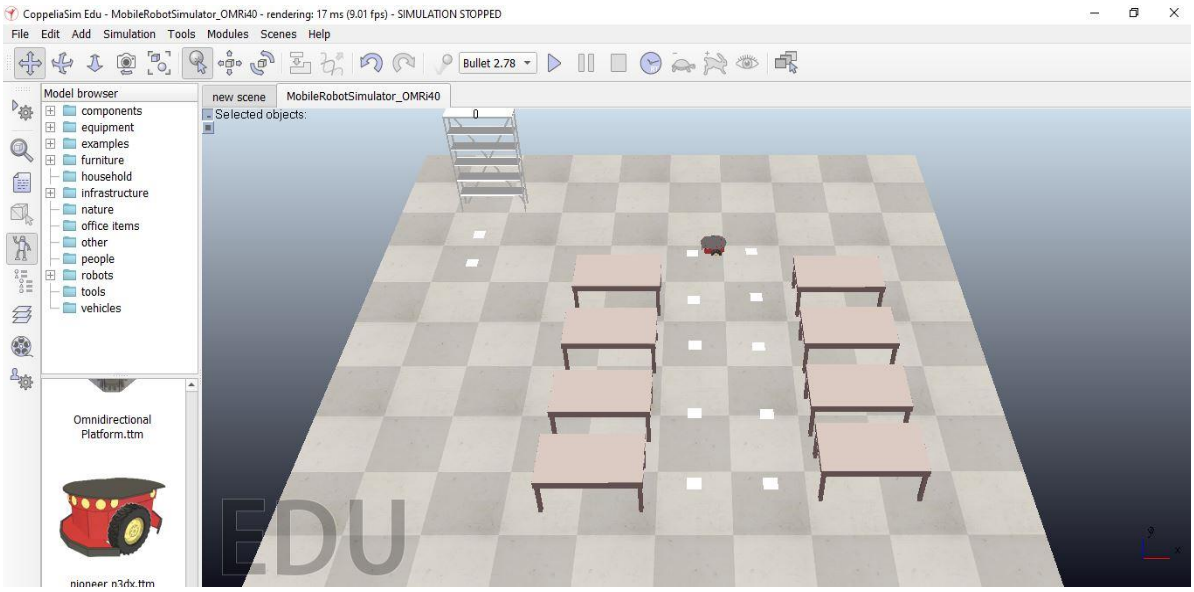


Figure 3.24. Simulation Environment of the OMRi40 - I

The CoppeliaSim environment in Figure 3.24 includes a mobile robot, a warehouse shelving unit, 8 tables and 12 tags. The tags represent both QR tags and RFID tags. Figures 25 and 26 show images of the robot simulation environment from different angles.

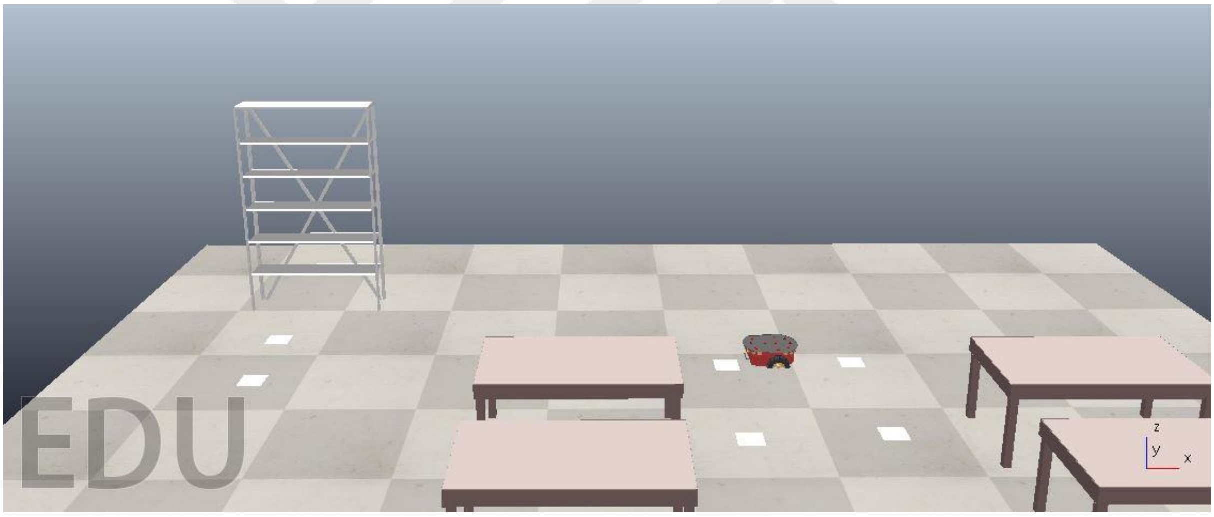


Figure 3.25. Simulation Environment of the OMRi40 – II

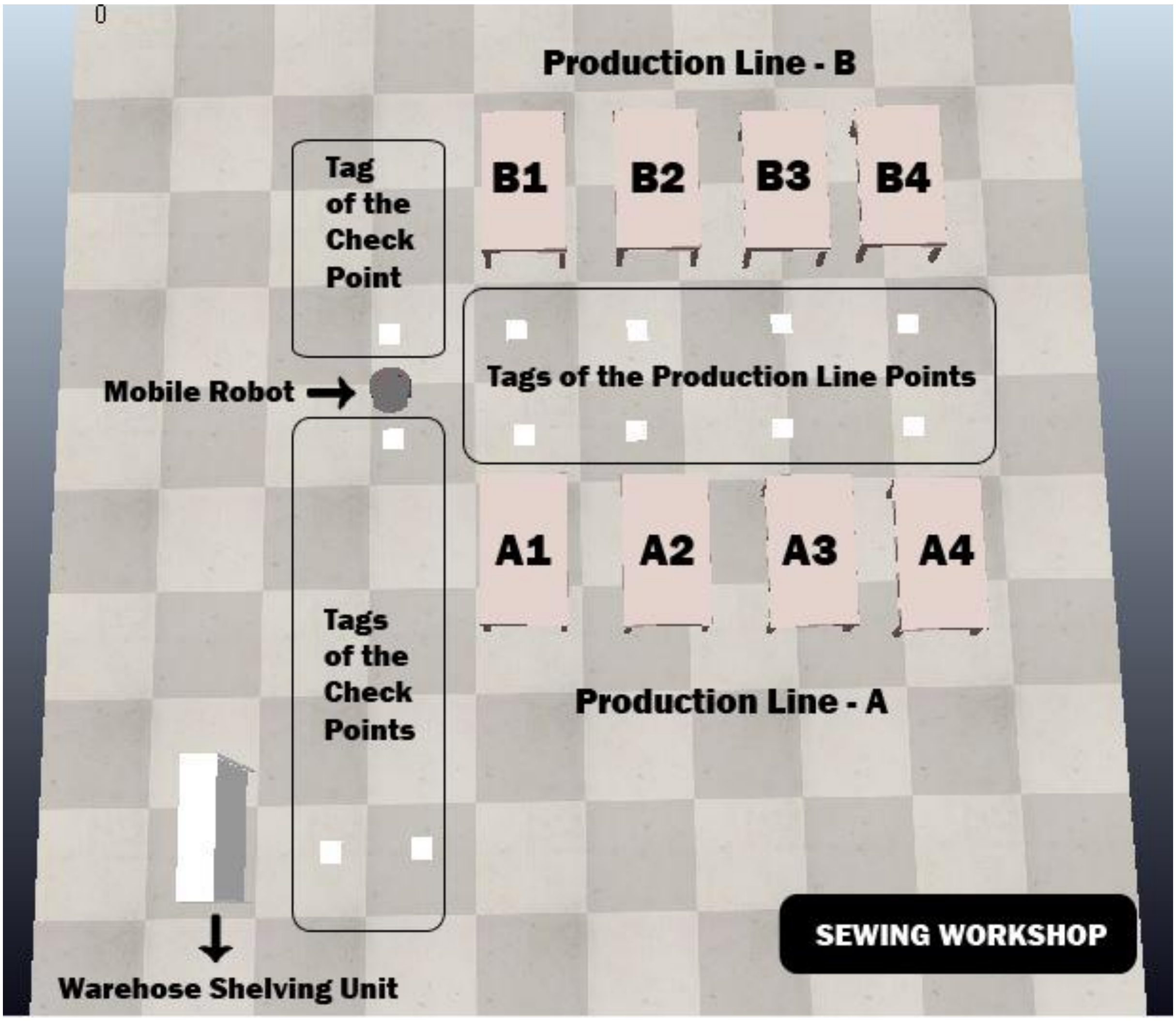


Figure 3.26. Simulation Environment of the OMRi40 – III

The present study uses two different use case scenarios to test the performance of the QR and RFID tags read by sensors. For this reason, both QR and RFID sensors are used analogously to read the tags in the simulation environment. Four of the tags are check-points and eight of the tags are production line points. With each tag read by the sensors on the mobile robot, the location information is updated and it is checked whether the targeted production line point has been reached. Information about the sensors is given below.

The Barcode/QR Code Scanner Module sensor in Figure 3.27 has a USB and UART communication interface and can be connected directly to a computer or easily integrated into embedded systems. It has the ability to read various common 1D/2D codes such as barcode or QR code. It has an inbuilt light source so it works even in the dark.

Figure 3.27. Barcode/QR Code Scanner Module (1D/2D Codes Reader)

The USB RFID Card - Tag Reader sensor in Figure 3.28 has a frequency of 13.56MHz and a plug and play feature with USB cable connection. It also supports Mifare1 S50, mifare1 S70 mifare ultralight, mifare pro and mifare desfire card types.

Figure 3.28. USB RFID Card - Tag Reader

The results of the usage scenarios performed are in the Research Findings and Discussion section of this thesis.

3.2.Material and Method of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution

The methodology of this section was presented at 12th International Conference on Industrial Technology and Management (ICITM 2023) within the scope of our study (Uğuz, Özyer, & Coşkunçay, 2023). Here, a comprehensive analysis was made using the topic modeling method on the basis of which academic studies in the field of mobile robots were carried out before and after the emergence of Industry 4.0. These analyses revealed the current research trends in the field of mobile robots, so that it can be said that the present study sheds light on future prospects in this field.

In this study, 13,404 articles in the field of mobile robots published in the Scopus database are discussed. These articles, which appeared in the last twenty years (2002-2021), are split into two groups: ten years before and ten years after 2011, when the concept of Industry 4.0 emerged. It has been examined how the theoretical and applied studies in both the academic community and among industry stakeholders have evolved, how they have changed and what trends have come to the fore. In addition to Industry 4.0, changes in research subjects such as path planning, navigation, task planning and semantic ontology in the field of mobile robots relating to the developing technology were observed via the topic modeling technique. In addition, the topic modeling titles created with the LDA MALLET model were associated with bibliometric analyses and research trends in this area examined within the framework of the research questions.

At this stage, the effect of mobile robot studies in the period of the emergence of the Industry 4.0 revolution were examined. The trends in academic studies in the field of mobile robots during the ten years before (2002-2011) and after (2012-2021) the emergence of Industry 4.0 were analyzed and shared with the academic community and industry stakeholders, aiming to find answers to the following important research questions for each period:

RQ1: What are the popular research topics in each period?

RQ2: What are the new trends in recent decades?

RQ3: What are the top five most cited research topics in each period?

RQ4: Who are the top five most productive authors in each period?

RQ5: What are the top five most productive countries in each period?

To answer these questions, article data were collected from the Scopus database, the largest peer-reviewed literature and citation database. Using the article query in Figure 3.29, a total of 14,581 papers were obtained:

Enter query string

TITLE-ABS(("mobile robot*" OR "automated guided vehicle" OR "autonomous mobile robot") AND ("industry*" OR "industry 4*" OR "industrial" OR "internet of things" OR "cloud*" OR "cloud comp*" OR "task plan*" OR "path plan*" OR "navigation" OR "ontology" OR "knowledge base" OR "semantic comp*" OR "semantic")) AND (LIMIT-TO(PUBYEAR,2021) OR LIMIT-TO(PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO(PUBYEAR,2018) OR LIMIT-TO(PUBYEAR,2017) OR LIMIT-TO(PUBYEAR,2016) OR LIMIT-TO(PUBYEAR,2015) OR LIMIT-TO(PUBYEAR,2014) OR LIMIT-TO(PUBYEAR,2013) OR LIMIT-TO(PUBYEAR,2012) OR LIMIT-TO(PUBYEAR,2011) OR LIMIT-TO(PUBYEAR,2010) OR LIMIT-TO(PUBYEAR,2009) OR LIMIT-TO(PUBYEAR,2008) OR LIMIT-TO(PUBYEAR,2007) OR LIMIT-TO(PUBYEAR,2006) OR LIMIT-TO(PUBYEAR,2005) OR LIMIT-TO(PUBYEAR,2004) OR LIMIT-TO(PUBYEAR,2003) OR LIMIT-TO(PUBYEAR,2002)) AND (LIMIT-TO(LANGUAGE,"English"))

Figure 3.29. Scopus Query String

Among these papers, only the Conference Papers and Articles in the scientific journals were discussed. As a result of this filtering, 13,414 articles remained. A check for nan values was made in the Title and Abstract columns of 13,414 papers: no nan values were found. Afterwards, it was checked whether the same papers were repeated in the Title and Abstract columns. The removal of such duplicate information left 13,404 papers remaning. Between 2002 and 2011, 4,687 papers were published, 3,556 of which were Conference Papers and 1,131 were Articles. Between 2012 and 2021, there was a total of 8,717 papers, 5,775 of which were Conference Papers and 2,942 of which were Articles. Thus, the number of papers in the last ten years is approximately twice as large as that in the latter ten years. The distribution of papers for the years 2002-2021 is shown in Figure 3.30.

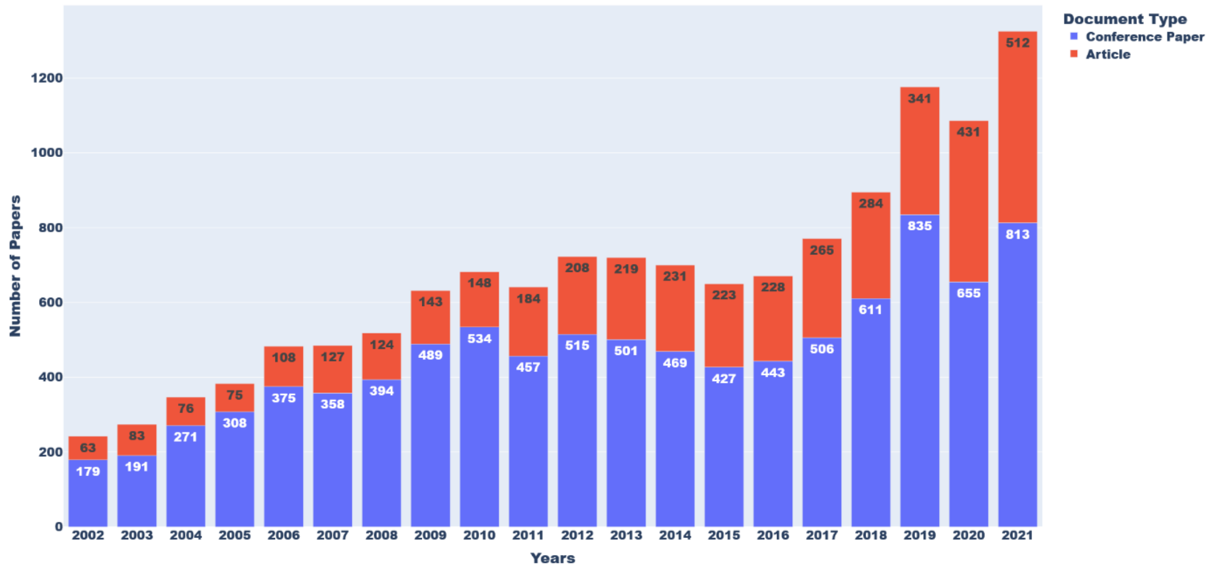


Figure 3.30. Distribution of Papers by Years

With the emergence of the Industry 4.0 Revolution in 2011, the usage areas of mobile robots have expanded further, and R&D studies in this field, both academically and in the industry, increased day by day. This study consists of text mining and bibliometric analyses. The outputs of the analyses are discussed in detail in the Research Findings and Discussion section.

Python programming language was used in all analyses of this study. Google Colaboratory was preferred as integrated development environment (IDE) for Python. Natural Language Toolkit (NLTK), LDA and MALLET libraries were used in the topic modeling (text mining) phase, Pandas and Numpy libraries for bibliometric analysis, and Matplotlib and Plotly libraries for data visualization.

4. RESEARCH FINDINGS AND DISCUSSION

The section Research Findings and Discussion is presented here under two main subtitles. The first of these, *Research Findings and Discussion of the Ontology Based Mobile Robot System for Industry 4.0 (OMRi40)*, shows test results of the OMRi40. The second main subtitle is *Research Findings and Discussion of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution* indicates the results of the topic modeling and bibliometrics analyses.

4.1. Research Findings and Discussion of the Ontology Based Mobile Robot System for Industry 4.0 (OMRi40)

In this part of the thesis, the tests of the OMRi40 Framework, which was developed in the Material and Method section, were carried out. The tests consist of usage scenarios developed for a smart textile factory in the Industry 4.0 concept and were carried out to make the OMRi40 Framework workable in a simulation environment. The development of the simulation environment is still continuing. Once the simulation environment of the OMRi40 Framework has been stabilized, it will also be tested in a real mobile robot environment. The OMRi40 Framework developed within the scope of this thesis was tested on dummy data in Figure 4.1 and the results are reported in this section.

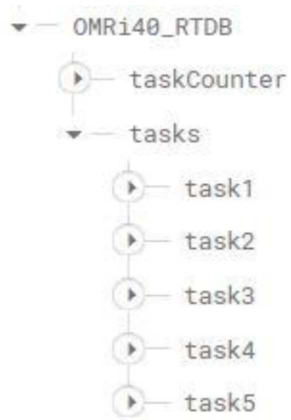


Figure 4.1. Dummy Data on the Firebase Realtime Database

In Figure 4.2, the tasks data in the Firebase Realtime Database are read with the GetTaskList function in the Python script.

```
def GetTaskList(notAnalyzed):
    ref = db.reference('/OMRi40_RTDB/tasks')
    snapshot = ref.order_by_child('isAnalyzed').equal_to(0).get()

    return snapshot
```

Figure 4.2. Dummy Data on the Firebase Realtime Database

As a result of the data preprocessing applied after the function is run, the taskID, timestamp, timestampRanked, materialPriorityValue, productionLinePoint and productionLinePointSDV information shown in Table 3 were obtained.

Table 3. List of the Task Data - I

taskID	**timestamp**	**timestamp Ranked**	**Material PriorityValue**	**productionLine Point**	**productionLine PointSDV**
task1	17/11/2022 10:07:32.69521	1	3	PLPID_A2_4	4
task2	17/11/2022 10:07:32.26623	2	1	PLPID_B1_4	4
task3	17/11/2022 10:08:01.45163	5	3	PLPID_A1_3	3
task4	17/11/2022 10:07:57.78512	4	1	PLPID_A3_5	5
task5	17/11/2022 10:07:49.21467	3	2	PLPID_B3_6	6

The information in Table 4 is used on dummy data using the Python script of the functions specified in Algorithm 2.

Table 4. List of the Task Data - II

taskID	**materialType**	**initialPoint**	**targetPoint**	**priorityWeight**	**priorityWeight Ranked**
task2	Company_Tag	CheckPoint1	PLPID_B1_4	5	1
task4	Yarn	PLPID_B1_4	PLPID_A3_5	6	2
task5	Company_Tag	PLPID_A3_5	PLPID_B3_6	7	3
task1	Laundry_Tag	PLPID_B3_6	PLPID_A2_4	9	4
task3	Laundry_Tag	PLPID_A2_4	PLPID_A1_3	11	5

The priorityWeight values in Table 4 are shown in order in the priorityWeightRanked column. According to this order, the taskID order has changed. Thus, the multi-task path planning route of the mobile robot is ready.

Table 5. Analysis of the Task Data

taskID	priority Weight Ranked	initialPoint	targetPoint	Number of Tags between Points	Processing Time (with QR Code Scanner)	processingTime (with RFID Tag Reader)
task2	1	CheckPoint1	PLPID_B1_4	4	162 sec.	198 sec.
task4	2	PLPID_B1_4	PLPID_A3_5	3	80 sec.	99 sec.
task5	3	PLPID_A3_5	PLPID_B3_6	1	12 sec.	13 sec.
task1	4	PLPID_B3_6	PLPID_A2_4	2	18 sec.	21 sec.
task3	5	PLPID_A2_4	PLPID_A1_3	1	11 sec.	29 sec.

In Table 5, two different usage scenarios of the same task list, QR Code Scanner and RFID Tag Reader, were tested. According to these results, data transactions made with QR Code Scanner were faster in seconds compared to RFID Reader. The processing time includes a +/- 10% margin of error.

4.2. Research Findings and Discussion of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution

The results of this section were presented at 12th International Conference on Industrial Technology and Management (ICITM 2023) within the scope of our study (Uğuz, Özyer, & Coşkunçay, 2023). The results of text mining and bibliometric analyses reported here are intended to find answers to the research questions.

4.2.1. Text Mining Analysis

In the text mining analysis part, topic modeling studies were carried out by first creating LDA and LDA MALLET models. The coherence values of these models are shown in Table 6. According to the results in Table 6, the coherence values of the LDA MALLET model give better results for both periods.

Table 6. Coherence Scores of Models between 2002-2011 and 2012-2021

Periods	LDA Score Results	LDA MALLET Score Results
2002-2011	0.4576	**0.4635**
2012-2021	0.4618	**0.4792**

The coherence values of the LDA MALLET models in Table 6 are given in Figures 4.3 and 4.4.

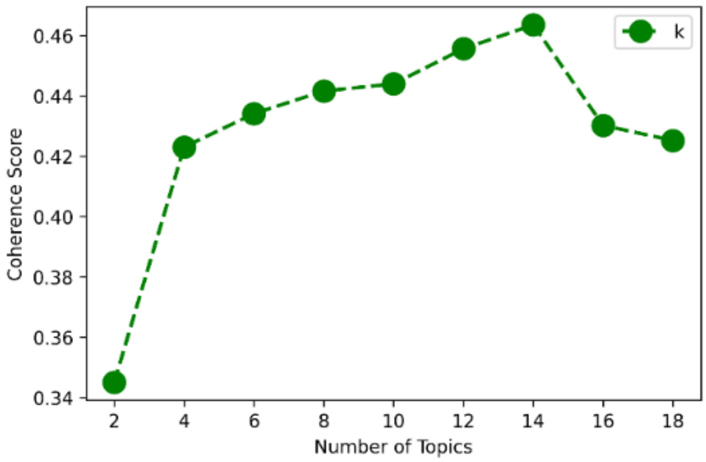


Figure 4.3. Number of Topics vs Coherence Score in 2002-2011

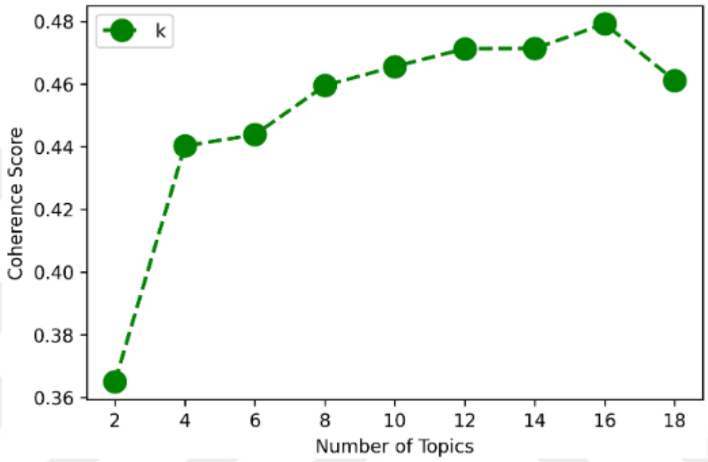


Figure 4.4. Number of Topics vs Coherence Score in 2012-2021

The highest coherence values in Figures 31 and 32 give the optimum number of topics (k value). The distribution of the paper counts for each of these topic names is given in Figures 4.5 and 4.6 separately for each period.

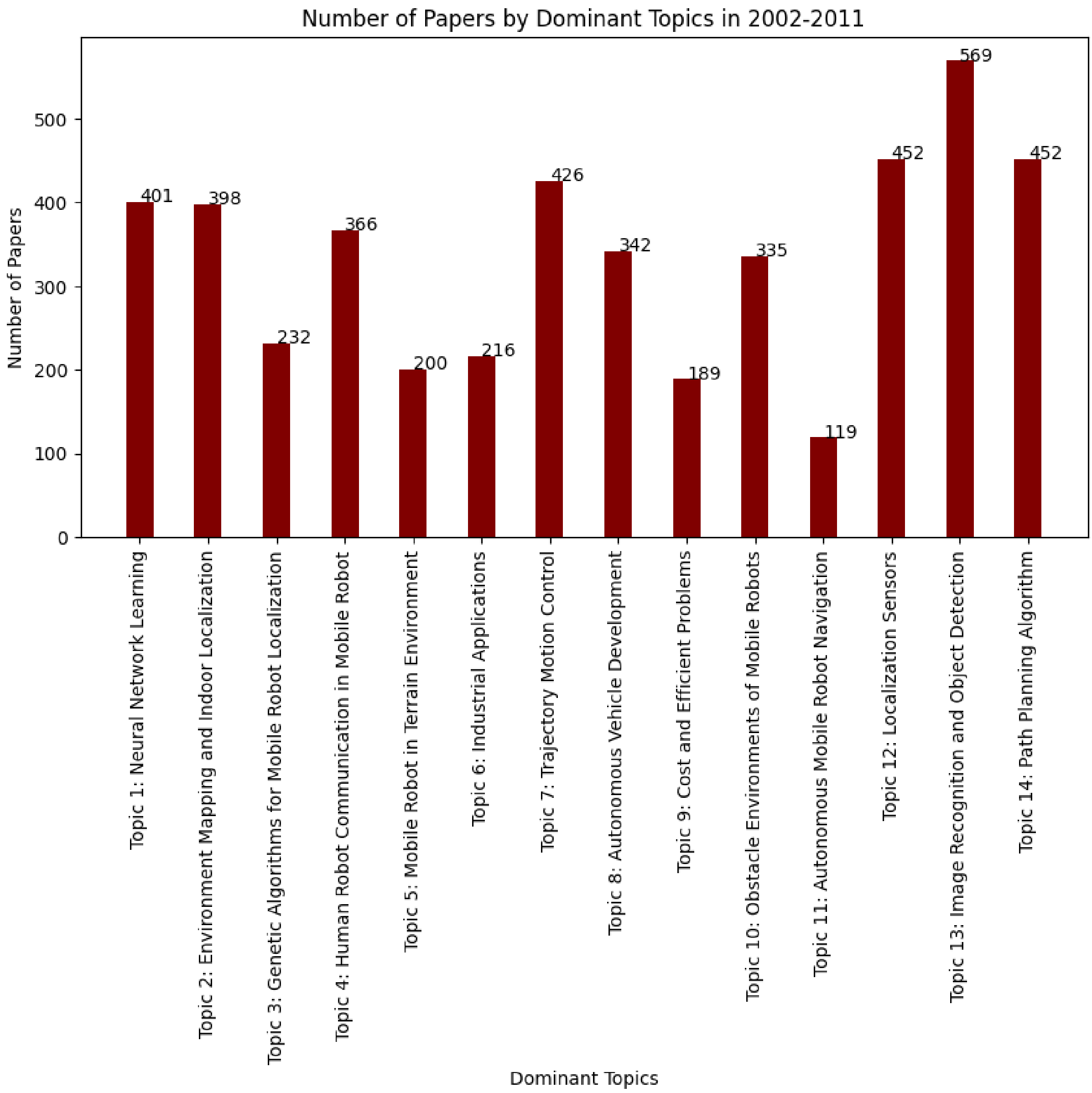


Figure 4.5. Number of Papers by Dominant Topics in 2002-2011

Based on first ten keywords that are dominant for each topic, a topic inference was made about the field to which the topics belong according to the keywords. Topic names for each keyword group are included in Figures 4.5 and 4.6, with the number of papers.

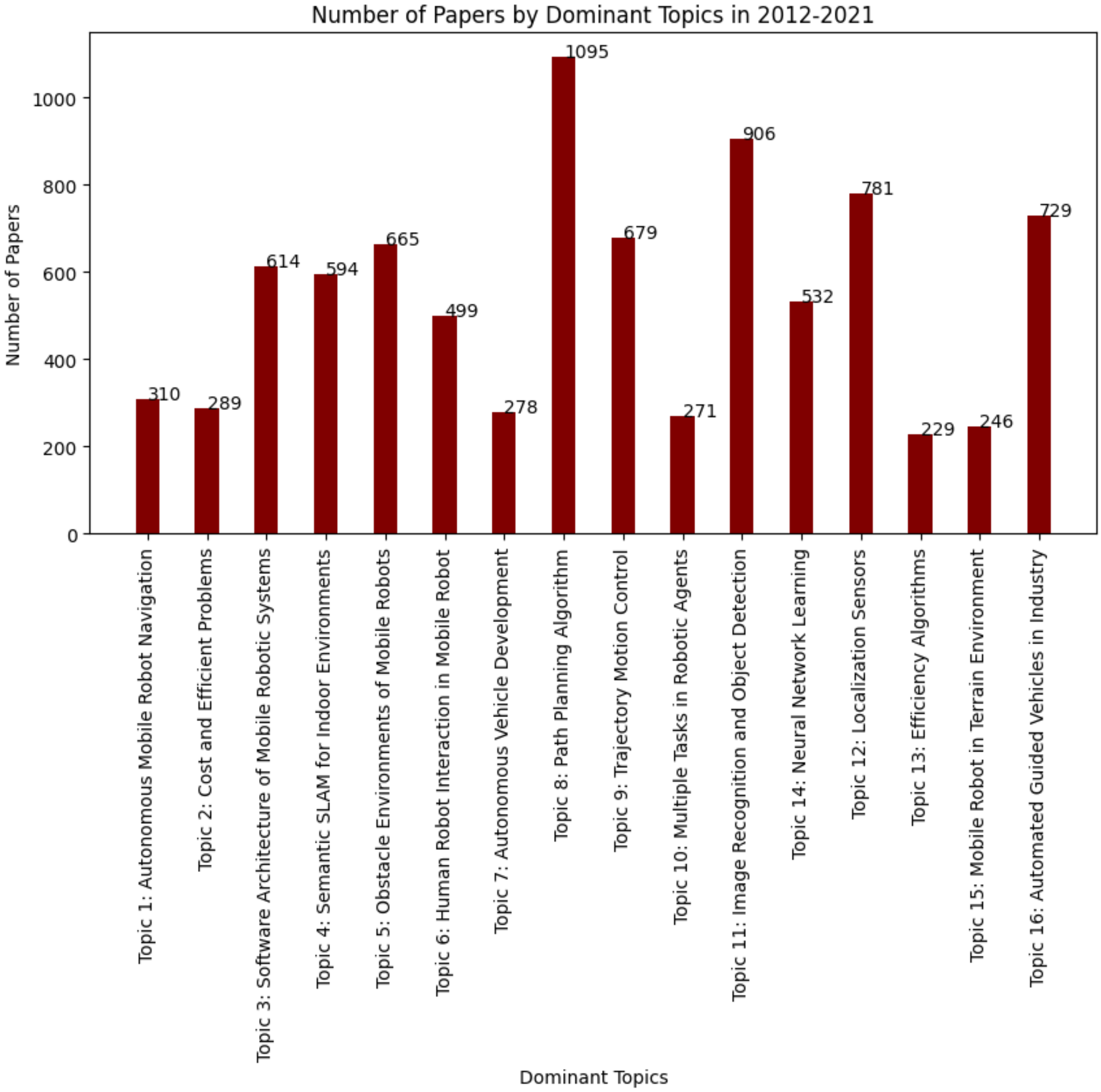


Figure 4.6. Number of Papers by Dominant Topics in 2012-2021

Figures 4.5 and 4.6 show there to be ten common topics in both periods: Neural Network Learning, Mobile Robot in Terrain Environment, Trajectory Motion Control, Autonomous Vehicle Development, Cost and Efficient Problems, Obstacle Environments of Mobile Robots, Autonomous Mobile Robot Navigation, Localization Sensors, Image Recognition and Object Detection, and Path Planning Algorithm.

Topics that are included in Figures 4.5 but not in Figures 4.6 are as follows: Environment Mapping and Indoor Localization, Genetic Algorithms for Mobile Robot Localization, Human Robot Communication in Mobile Robot, and Industrial Applications.

Topics that are included in Figures 4.6 but not in Figures 4.5 are as follows: Software Architecture of Mobile Robotic Systems, Semantic SLAM for Indoor Environments, Human

Robot Interaction in Mobile Robot, Multiple Tasks in Robotic Agents, Efficiency Algorithms, and Automated Guided Vehicles in Industry.

The new research topics in Figure 34 seem quite interesting. In addition, according to Table 7, it seems likely that further studies on Automated Guided Vehicles in Industry will emerge as a new trend that has come to the fore in the last ten years. Moreover, this new trend has ranked 4th, displacing Trajectory Motion Control, which was ranked 4th in the first 10-year period. It may be concluded that the smart factory transformation that emerged with Industry 4.0 is an important factor in the coming to the forefront of Automated Guided Vehicles in Industry.

Table 7. The Top 5 Research Topics in Each Period

No.	2002-2011		2012-2021	
	Research Topic	Paper Count	Research Topic	Paper Count
1	Image Recognition and Object Detection	559	Path Planning Algorithm	1095
2	Localization Sensors	452	Image Recognition and Object Detection	906
3	Path Planning Algorithm	452	Localization Sensors	781
4	Trajectory Motion Control	426	Automated Guided Vehicles in Industry	729
5	Neural Network Learning	401	Trajectory Motion Control	679

In addition, when Table 7 is continued to be examined, it seems that the Path Planning Algorithm issue has taken first place in the last ten years. It can be stated that studies on the topic of Automated Guided Vehicles in Industry contributed to the rise of this topic to first place, because Automated Guided Vehicles need to have the most suitable route to perform the tasks in the workflow. Therefore, the topic of Path Planning for Automated Guided Vehicles has an important place.

4.2.2. Bibliometric Analysis

Bibliometric analysis provided various results were obtained regarding research topics, authors, institutions and countries between 2002-2011 and 2012-2021 periods.

The results of these analyses provide important insights into the work done in the field of mobile robotics. In particular, the number of citations plays an important role in bringing scientific publications to the fore. Figure 4.7 and 4.8 show the Citation values according to the Dominant Topic numbers. The first five dominant topics with high citation values for both the first ten years and the last ten years are shown in Table 8.

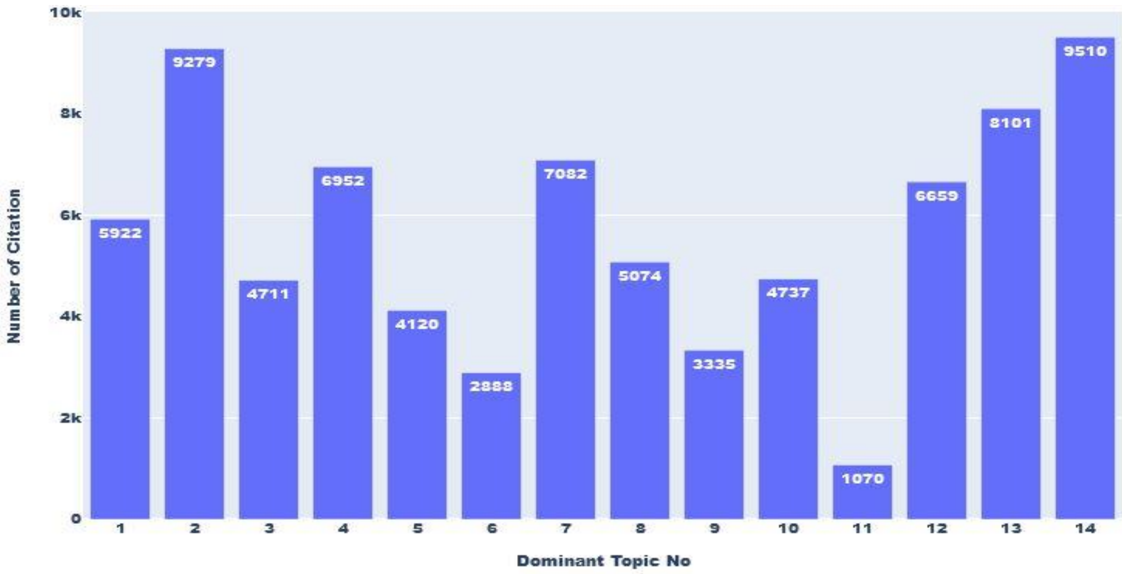


Figure 4.7. Number of Citation by Dominant Topic No. in 2002-2011

When Figure 4.7 is examined, the first three dominant research topic numbers with high citation numbers are 14 (Path Planning Algorithm), 2 (Environment Mapping and Indoor Localization) and 13 (Image Recognition and Object Detection), respectively. In addition, the top five dominant research topics with the highest citation numbers are shown in Table 8 for the first decade.

As shown in Figure 4.8, the top three dominant research topic numbers with high citation numbers are 8 (Path Planning Algorithm), 11 (Image Recognition and Object Detection) and, 13 (Localization Sensors), respectively. In addition, the top five dominant research topics with the highest citation numbers are shown in Table 8 for the second decade.

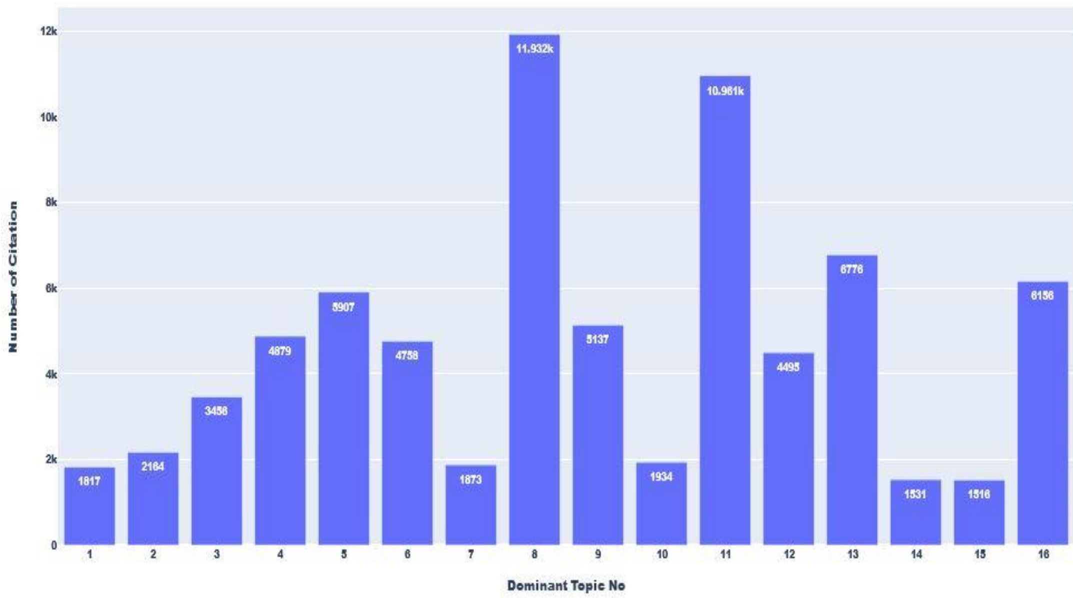


Figure 4.8. Number of Citation by Dominant Topic No. in 2012-2021

Considering the first three dominant research topics with the highest citation value in Figures 4.7 and 4.8, there are two dominant research topics that are common to both. These are Path Planning Algorithm, and Image Recognition and Object Detection, respectively. These two topics are included in the top five topics with the highest number of papers in both periods in Table 7. There is an interesting situation here. Although the number of articles in the topic Image Recognition and Object Detection was higher in the first 10-year period, this topic could not take first place in respect of the number of citations. As seen in Table 8, the citation number of the topic Path Planning Algorithm took first place. Moreover, another remarkable situation is that the citation number of the topic Path Planning Algorithm in the first decade is high, shedding light on the choice of studies to be carried out in these areas in the following years. One of the most important proofs of this situation is that the number of studies conducted in the field of Path Planning Algorithm rose to first place in the second decade.

Table 8. The Top 5 Most Cited Research Topics in Each Period

No.	2002-2011		2012-2021	
	Research Topic	Citation Count	Research Topic	Citation Count
1	Path Planning Algorithm	9510	Path Planning Algorithm	11932
2	Environment Mapping and Indoor Localization	9279	Image Recognition and Object Detection	10961
3	Image Recognition and Object Detection	8101	Localization Sensors	6776
4	Trajectory Motion Control	7082	Automated Guided Vehicles in Industry	6156
5	Human Robot Communication in Mobile Robot	6952	Obstacle Environments of Mobile Robots	5907

Table 8 shows the research topics with the highest citation value in both periods. Three of the research topics in the first 10-year period also figure in the research topics with the highest number of articles in the first 10-year period in Table 7, as do four of the research topics in the second 10-year period in the research topics with the highest number of papers in the second 10-year period in Table 7. Thus, there may be an increase in the number of citations on topics with a high number of papers.

Table 9. The Top 5 Most Productive Authors in Each Period

No.	2002-2011		2012-2021	
	Author	Total Contribution Rate	Author	Total Contribution Rate
1	Yang S. X.	11.75	Parhi D. R.	14.48
2	Burgard W.	8.78	Mohanty P.K.	7.67
3	Parhi D. R.	6.18	Savkin A. V.	7.17
4	Siegwart R.	6.11	Burgard W.	5.93
5	Savkin A. V.	5.42	Chung W.	5.62

Table 9 includes the top five most productive authors and their total contribution rate in both periods. Burgard W., Parhi D. R. and Savkin A. V. succeeded in taking part in both periods. The productivity of Parhi D. R. has increased more and has taken first place in the second decade. Mohanty P.K. and Chung W. are included instead of Yang S. X. and Siegwart R. in the last 10-year period.

Table 10. The Top 5 Most Productive Countries in Each Period

No.	2002-2011		2012-2021	
	Country	Total Contribution Rate	Country	Total Contribution Rate
1	China	609.55	China	1909.82
2	United States	571.54	United States	675.05
3	Japan	423.33	India	607.10
4	South Korea	358.86	Germany	481.49
5	Germany	275.36	Japan	385.06

Table 10 shows the top five most productive countries in both periods. Four countries appear in both periods. South Korea, which is among the top five countries in the first 10-year period, has left its place to India in the last 10-year period. In addition, India ranked 3rd, ahead of Japan and Germany. China and the United States retained their places, ranking 1st and 2nd, respectively. Germany was ahead of Japan in the second decade. The rise of India in the last ten years as shown in Table 10 is worthy of attention.

5. CONCLUSION AND RECOMMENDATIONS

In this part, the Conclusion and Recommendations are given under two main subheadings: *Conclusion and Recommendations of the Ontology Based Mobile Robot System for Industry 4.0 (OMRi40),* and *Conclusion and Recommendations of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution***.**

5.1. Conclusions and Recommendations of the Ontology Based Mobile Robot System for Industry 4.0 (OMRi40)

In this thesis, a new framework named Ontology Based Mobile Robot System for Industry 4.0 that can be used in Industry 4.0 applications, has been developed. This framework consists of Cloud Computing Services, Ontology and Algorithm, and Simulation Environment main layers. It has been successfully completed in the testing phase of the OMRi40 framework. RFID and QR code tags were successfully read by the sensors (RFID and QR code readers) integrated into the simulation environment of the mobile robot and communicated to the cloud computing services. During the multi-tasking of the mobile robot, the target points that the mobile robot should go to first were established by the task priority algorithm and ontology.

The OMRi40 framework permits instant data to be produced and recorded by the mobile robot and the staff in the sewing workshop. The processed data come ready for analysis using the Python scripts. The Task Priority algorithm is applied to the data, and the data kept in the Fuseki Server. In line with the mobile robot's request for the next task using the Multi-task Path Planning algorithm, the RDF query is run and the current path information presented. All these processes have been tested and successfully carried out by OMRi40 framework.

This thesis study has three limitations. The first of these is that the OMRi40 framework developed has not been tested with a real data set. If the data set were real, both the efficiency and use of the algorithms in OMRi40 would be better tested depending on the usage scenarios, and the performance of the OMRi40 framework could be tested on a large number of tasks. The second limitation is that the usage scenarios employed consider that only one mobile robot in the sewing workshop is tested. The sharing of multi-tasks by multi-mobile robots to reach the target points was not carried out in this study. The third limitation is that path planning takes place in a static rather than a dynamic manner. Before the mobile robot starts the tasks, the task list was analyzed and sorted according to the task priority algorithm. Once the mobile robot has started its task, the priority algorithm is not calculated over and over for each tag it reads in the workshop. For this reason, the mobile robot performs the tasks statically from the moment it starts moving from the initial point.

In future studies, using the OMRi40 framework, it is planned to use the algorithms with real task datasets, to create use case scenarios in the simulation environment and apply them to real multi-mobile robots in the real world. In addition, the tasks that the mobile robot performs statically can be made dynamic. This would permit observation of the kind of differences existing in the static and dynamic realization of the tasks. With machine learning algorithms that can be applied to real task datasets, which will become big data, the estimated completion time of the task process can be estimated. This can contribute to increasing efficiency and minimizing time loss in the production stages of smart factories in the Industry 4.0 concept.

5.2. Conclusion and Recommendations of the Topic Modeling Analysis for Mobile Robots within the Periods Before and After the Industry 4.0 Revolution

The conclusion of this section was presented at 12th International Conference on Industrial Technology and Management (ICITM 2023) within the scope of our study (Uğuz, Özyer, & Coşkunçay, 2023). Mobile robots are at the forefront of studies in the field of robotics, and the situation has become more important with the increase in today's usage areas. With the emergence of Industry 4.0, academic and industrial R&D studies in the field of mobile robots continue to increase day by day. In the present study, the abstracts of 13,404 papers collected from the Scopus database were examined over two 10-year periods between 2002-2011 and 2012-2021. The year 2011, when Industry 4.0 emerged, has been determined as a turning point. For this reason, it has been examined in which direction the studies in the field of mobile robots have progressed and what changes occurred in the time before and after the emergence of the concept of industry 4.0. The analyses indicated the studies in the field of mobile robots are indeed related to the developments in the field of industry 4.0.

Topic modeling analyses were carried out using the LDA MALLET model for both periods. The top five research topics that came to the fore in both periods are examined. Image Recognition and Object Detection, Localization Sensors, Path Planning Algorithm and Trajectory Motion Control were among the popular research topics that come into prominence in both periods. In addition, it was concluded that the research topic Automated Guided Vehicles in Industry is at the forefront of the second period as a result of the developments that occurred with the emergence of industry 4.0. Software Architecture of Mobile Robotic Systems, Semantic SLAM for Indoor Environments, Human Robot Interaction in Mobile Robot, Multiple Tasks in Robotic Agents, and Efficiency Algorithms research topics, together with Automated Guided Vehicles in Industry can also be specified as prominent new trends in the second 10-year period.

The top five most cited research topics for both periods were explored. The most striking situation here is that the Path Planning Algorithm research topic is in first place in respect of the number of citations in both periods. It is also noteworthy that the research topic Automated Guided Vehicles in Industry emerged in the second period and is one of the most cited research topics. In addition, the top five most productive authors of both periods were examined. Those whose work came to the forefront in both periods are Burgard W., Parhi D. R. and Savkin A. V. The academic studies of Parhi D. R. in the field of mobile robots came to the forefront in the second ten years. In addition, the top five most productive countries for both periods were analyzed. When the productivity of the countries to which the authors' academic studies are affiliated were examined, China and the United States were seen to have risen to prominence by taking first and second places in both periods. In addition, Japan and Germany also succeeded to take place in both periods. India did not figure in the first period, but did so in the second period, and as such was the country that attracted attention.

In this study, the evolution of research topics in the field of mobile robots within the scope of before and after industry 4.0 revolution was examined and shared with the academy and industry community who will carry out future studies in this field. As a future comprehensive study, a study of text mining and bibliometric analyses that only includes the keyword mobile robot may be carried out.

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