Journal of Smart Systems Research | e-ISSN: 2757-6787

Volume: 3 | Number: 1 | Year: 2022

Table of Contents

Research Article
Journal of Smart Systems Research (JOINSSR) 3(1), 1-10, 2022
Recieved: 03-January-2022 Accepted: 14-January-2022

SAKARYA UNIVERSITY OF APPLIED SCIENCES

Osmanlıcadan Türkçeye Uçtan Uca Aktarım

İshak Dölek[1*], Atakan Kurt[2]

[1]Bilgisayar Mühendisliği, Mühendislik Fakültesi, İstanbul Ün-Cerrahpaşa, Türkiye, ishakdolek54@gmail.com

[2]Bilgisayar Mühendisliği, Mühendislik Fakültesi, İstanbul Ün-Cerrahpaşa, Türkiye, atakan.kurt@istanbul.edu.tr

ÖZET

Bu makalede Osmanlıca Dokümanların Modern Türkçeye Uçtan Uca aktarım çalışması sunulmuştur. Devlet arşivleri, kütüphaneleri ve özel koleksiyonlarda milyonlarca Osmanlıca doküman bulunmaktadır. Bunların Modern Türkçeye elle aktarımı mümkün değildir. Osmanlica.com adresinde kullanıma açılan bu çalışmada Osmanlıca dokümanların Modern Türkçeye 3 adımda aktarımı yapılmaktadır: (i) Osmanlıca karakter tanıma (OCR) (ii) Osmanlıca-Türkçe Alfabe Çevrisi (iii) Osmanlıca-Türkçe Dil Çevirisi. Bildiğimiz kadarıyla, bu çalışma Osmanlıca-Türkçe aktarım sürecinin üç adımını da çözmeyi hedefleyen ilk çalışmadır. Bu adımların her biri NLP ve Derin Öğrenmede teknik ve bilimsel olarak karmaşık ve kaynak gerektiren problemlerdir. Birinci adımda doküman görüntüleri OCR ile Osmanlı alfabesinde düz metine dönüştürülür. İkinci adımda Arap-tabanlı Osmanlı alfabesindeki bu metin bir alfabe çevrisi sistemiyle Latin-tabanlı Türk alfabesine dönüştürülür. Türk alfabesindeki metin her ne kadar okunabilir olsa da çok sayıda Arapça ve Farsça kelime ve yapılar barındırdığı için henüz anlaşılabilir değildir. Üçüncü adım bu metin makine çevirisi ile Modern Türkçeye aktarılır. Birinci adımda geliştirilen CRNN tabanlı OCR modeli 21 sayfalık bir veri setinde test edilmiş ve %96 karakter tanıma doğruluk oranı üretmiştir. İkinci adımda geliştirilen alfabe çeviri sistemi 7500 kelimelik bir veri setiyle test edilmiş ve %98 kelime çeviri doğruluk oranı üretmiştir. Üçüncü adım için kelime grubu tabanlı bir makine çeviri sistemi geliştirilmiş ve testlerine başlanmıştır. Bu çalışmanın tarihi, sosyal ve kültürel bir ihtiyaca katkı sağladığı için önemli ve değerli olduğunu düşünüyoruz.

Anahtar Kelimeler: Osmanlıca OCR, Osmanlıca-Türkçe alfabe çevirisi, Osmanlıca-Türkçe harfçevrim, Osmanlıca-Türkçe dil çevirisi

Ottoman-Turkish End to End Conversion

ABSTRACT

In this paper, a study titled End-To-End Conversion Ottoman Documents to Contemporary Turkish is presented. The state archives, libraries, and private collections contain millions of documents written in Ottoman. It is practically impossible to convert all these documents to Modern Turkish manually. In this work which is available at Osmanlica.com Ottoman documents are converted to Modern Turkish in three steps: (i) Ottoman OCR (Optical Character Recognition), (ii) Ottoman-Turkish transliteration, and (iii) Ottoman-Turkish translation. To our knowledge this is the only study to set out to solve all three steps of this conversion to date. Each one of these three steps are technically complex and resource-demanding problems in NLP and deep learning. OCR converts image files to editable text in Ottoman alphabet in the first step. Transliteration tranforms that Ottoman text in Arabic-based Ottoman alphabet to the Latin-based Turkish alphabet making it readable but not yet understandable because of Arabic and Persian words and structures in the second step. In the last step, this Ottoman text in Turkish alphabet is translated to Modern Turkish via machine translation. The CRNN based on model developed in the first step produced %96 OCR accuracy with a 21 pages test document set. The Ottoman-Turkish transliteration system

* Correspending Author's email: ishakdolek54@gmail.com

developed yielded %98 accuracy with a test set of 7500 words in the second step. The phase-based Ottoman-Turkish machine translation system developed in the third step is being tested presently. We believe that the contribution of this study is significant because it addresses an important social, cultural and scientific problem.

Keywords: Ottoman OCR, Ottoman-Turkish Transliteration, Ottoman-Turkish Translation

1 Giriş

Osmanlıca yaklaşık olarak 13. yüzyıldan 20. yüzyıla kadar Osmanlı İmparatorluğunda kullanılan bir yazı dilidir [1]. Günümüzde Latin (Roman) alfabesine geçiş yapıldığı ve kelimelerin çoğu kullanımdan kalktığı için Osmanlıcayı hem okumak hem de anlamak güçtür. Millî kültürümüzün temelini oluşturan eserlerin büyük bir kısmı Osmanlıcada yazılmıştır. Osmanlı arşiv ve kütüphanelerindeki kitap, dergi, gazete, defter, kayıt ve belgeler yüzlerce yıllık kültür, sanat ve tarih mirası içinde önemli bir yer tutar. Bu kaynaklarda saklı bilgiye hızlı, etkin ve doğru bir şekilde erişilmesi için başta OCR olmak üzere teknolojinin yardımına ihtiyaç vardır. TÜBİTAK destekli *Osmanlıcadan Günümüz Türkçesine Yapay Zekâ Destekli Uçtan Uca Aktarım Projesi* bu amaçla yapılan bir çalışmadır. Çalışmanın çıktıları Osmanlica.com sitesinden kullanıcılara sunulmuştur. Çalışma Tablo 1'de görüldüğü gibi bütüncül bir yaklaşımla Osmanlıca dokümanların 4 adımda bir uçtan diğer uca yani *dokümandan Türkçe metne* otomatik olarak çevrilmesi amaçlanmaktadır:

1. *Doküman-görüntü dönüşümü (document-image conversion, digitization)*: Dokümanın tarayıcı veya fotoğraf makinasıyla taranıp, sayısallaştırılması ve ardından JPG, PNG vb. görüntü dosya formatına çevrilmesidir. Bu adım sıradan bir işlem olduğundan çalışmaya dâhil değildir.
2. *Görüntü-metin dönüşümü (image-text conversion, OCR)*: Görüntü dosyasının görüntü işleme ve makina öğrenmesi ile Osmanlı Alfabesindeki Osmanlıca metne (editable text) dönüştürülmesi işlemidir.
3. *Osmanlıca-Türkçe Alfabe Dönüşümü (harfçevrim, machine transliteration)*: Osmanlı alfabesindeki Osmanlıca metnin Türk alfabesine, yani Latin Harfli Modern Türkçe alfabesine aktarımıdır.
4. *Osmanlıca-Türkçe Dil Çevirisi (intra-language machine translation)*: Türk alfabesindeki Osmanlıca metnin bilgisayarlı çeviriyle Modern yani günümüz Türkçesine çevirisidir. Çeviri sonucu ortaya Türk Alfabesinde Modern Türkçe metin çıkar.

Tablo 1: *Osmanlıca-Türkçe Uçtan-Uca Aktarım Örneği*

Adım (girdi → işlem → çıktı)	*Çıktı*
1. Doküman-görüntü dönüşümü: Doküman → sayısallaştırma → görüntü dosyası	انسانه صداقت یاقیشور کورسه‌ده ا کراه یاردمجیسیدر طوغریلرك حضرت الله
2. Osmanlıca OCR: Görüntü dosyası → OCR → Osmanlıca (Arap alf)	انسانه صداقت یاقیشر کورسه‌ده اکراه یاردمجیسیدر طوغریلرك حضرت الله
3. Alfabe dönüşüm: Osmanlıca (Arap alf) → dönüşüm → Osmanlıca (Latin alf)	İnsana sadâkat yakışır görse de ikrah Yardımcısıdır doğruların hazreti Allah
4. Dil çevirisi: Osmanlıca (Latin alf) → çeviri → Türkçe (Latin alf)	İnsana doğruluk yakışır görse de kötülük Yardımcısıdır doğruların Hazreti Allah

Bu makalede sunulan çalışma Osmanlıca-Türkçe aktarım problemini bütün olarak ele alan kendi türündeki ilk çalışma olup *Osmanlıca OCR, alfabe çevirisi* ve *dil çevirisi* olmak üzere üç adımdan ve her adım için geliştirilen 3 ayrı araçtan oluşmaktadır. Osmanlıca OCR için akademik çalışmalara [2] [3] ve ticari çalışmalara [4] [5] örnek verilebilir. Çalışmamızda geliştirdiğimiz Osmanlıca OCR modeli, Google Docs, Fine Reader, Tesseract Arapça ve Farsça, Miletos araçları ile karşılaştırılmıştır [6]. Model %96 karakter tanıma doğruluk oranıyla diğer araçlardan belirgin bir şekilde daha yüksek bir performans sağlamıştır. Kısıtlı sayıdaki Osmanlıca-Türkçe alfabe çevirisi çalışmalarına [7] [8] [9] örnek verilebilir. Çalışmamızda geliştirdiğimiz alfabe çevirisi aracıyla yapılan testlerde %98 doğruluk oranına ulaşılmıştır. Osmanlıca-Türkçe dil çevirisi alanında yapılan çalışmalara ise [10] örnek verilebilir. Çalışmamızda geliştirdiğimiz dil çeviri aracı aşağıda Bölüm 4'te özetlenmiş olup testlerine devam edilmektedir.

Osmanlıca-Türkçe aktarımın her adımı karmaşık ve güç bir problem olduğundan önceki çalışmalar bu adımlardan sadece birine veya belirli bir alt probleme yoğunlaşabilmiş durumdadır. Literatürde aktarım sürecinin tamamı üzerine yapılmış herhangi bir çalışma bulunmamaktadır. Osmanlıca OCR üzerinde yapılan çalışmalarda yukarıda belirtildiği üzere ticari araçlardan veya açık kodlu araçlardan daha yüksek bir doğruluk oranına henüz ulaşamamıştır. Osmanlıca-Türkçe alfabe çevirisi konusunda literatürde birkaç çalışma olsa da alfabe çevirisi OCR'dan daha güç bir problem olduğundan henüz ticari veya açık kodlu bir çeviri sistemi geliştirilememiştir. Osmanlıca-Türkçe dil çevirisi konusunda ise yapılmış çalışmalar küçük metin kümeleri üzerinde derin sinir ağlarının eğitilmesiyle üretilen modeller ile sınırlı kalmış ve Türkçe sondan eklemeli bir dil olduğundan testlerde henüz tatmin edici seviyede bir sonuç elde edilememiştir.

Makale şu şekilde organize edilmiştir: Bölüm 2'de Osmanlıca OCR, Bölüm 3'te Osmanlıca Türkçe Alfabe Çevirisi ve Bölüm 4'te Osmanlıca Türkçe Dil Çevirisi kısaca sunulmuştur. Sonuçlar ve özet Bölüm 5'te verilmiştir.

2 Osmanlıca OCR

Osmanlıca OCR bir resim dosyasında saklanan görüntüdeki karakterlerinin görüntü işleme ve makina öğrenmesi teknikleri kullanılarak metne dönüştürülmesi işlemidir [11]. Osmanlıca OCR genellikle 5 adımda gerçekleştirilir:

1. *Görüntü ön işleme (image preprocessing)*: Bu adım görüntü dosya formatının ve görüntü boyutunun normalleştirilmesi, gerekliyse metin fontunun ve boyutunun belirlenmesi, görüntünün filtrelenmesi, eşikleme (tresholding), siyah-beyaza dönüştürme (binarization), gürültü temizleme (noise reduction), görüntü zenginleştirme (image enhancement) vb. ön işlemleri içerir.

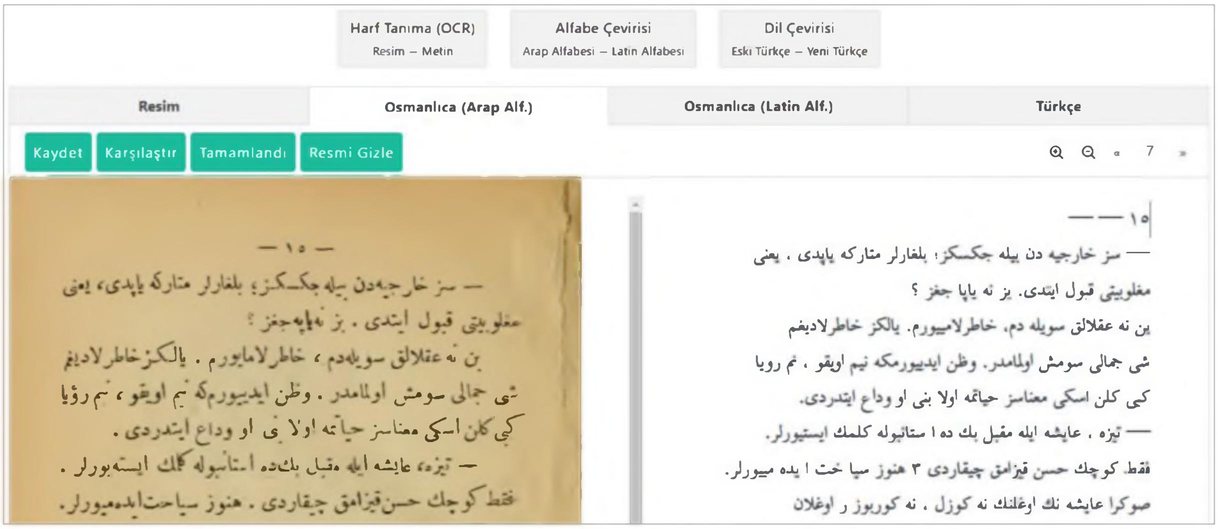
2. *Görüntü bölümleme (image segmentation)*: Tanıma işleminin yapılabilmesi için görüntünün tanınacak birimlere bölümlenmesi gerekmektedir. Görüntü öncelikle satırlara sonrasında kelime karakterlere bölümlenir.

3. *Özellik çıkarma (feature extraction)*: Tanıma işlemi bir sınıflandırıcı modelle yapıldığından, modeli eğitmek için kullanılacak özelliklerin baştan bir defa belirlenmesi gerekmektedir. Çok katmanlı CNN tabanlı derin sinir ağlarında özellik çıkarma model eğitiminin içinde gerçekleşmektedir.

4. *Tanıma (recognition, OCR)*: Tanınmak istenen birimin (eğri, karakter, karakter katarı, kelime, vb.) bir sınıflandırıcı model kullanılarak tanınması işlemidir. Tanima için CNN ve RNN sinir ağlarını birleştiren bir derin öğrenme modeli kullanılmıştır.

5. *Düzenleme ve hata düzeltme (post processing & error correction)*: Tanıma adımından sonra OCR çıktısındaki karakterlerin normalizasyonu ve OCR'da tanınmamış karakter veya kelimelerin tahmini için yapılan düzenleme ve hata düzeltme işlemleridir.

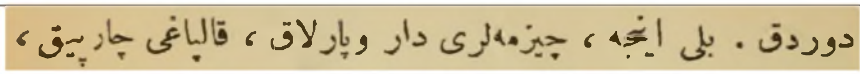
Osmanlıca dokümanlarda OCR çalışması Arapça ve Farsçaya göre daha zor bir problemdir. Osmanlıca OCR için bu zorlukları ikiye ayırabiliriz. (i) dil bağımsız ve (ii) dil bağımlı zorluklar. OCR probleminde dilden bağımsız olarak başarı oranını görüntü çözünürlüğü, görüntü kalitesi, yazı fontu, veri seti, sözlük vb. birçok etken söz konusudur. Dil-bağımlı zorluklar arasında Osmanlıca alfabesindeki harflerin kavisli olması, harflerin bitiştirilmesi, harflerin konuma göre farklı şekillere sahip olması, harfler arasında benzerliğin yüksek olması, harflerin yığılarak yazılabilmesi vb. durumlar söz konusudur. Osmanlıca OCR için geliştirilen sistemin ara yüzü Şekil 1'de verilmiştir. Ara yüzde OCR yapılan dokümanın resim ve OCR çıktısı yan yana gösterilmektedir.



Şekil 1: Osmanlıca OCR aracı

OCR işleminden önce dokümandaki süslü kenarlıklar, çerçeveler, şekiller vb. kaldırılması gerekmektedir. OCR'dan sonra elde edilen metin üzerinde metin normalizasyonu, bölütlenmiş kelimelerin düzeltilmesi, yazım hatalarının düzeltme gibi işlemleri uygulanarak hatalar düzeltilir. Tablo 2'de OCR'daki tanıma hatalarına bir örnek verilmiştir. Bu örnekte Osmanlıca dokümandan bir satır resim, referans yani doğru metin (ground truth) ve OCR'da hesaplanan metin paralel olarak verilmiştir. İşlem satırında ↕ değişim, ↓ ekleme, ↑ silme anlamına gelmektedir. Osmanlıca resim OCR yapıldıktan sonra noktalama işaretleri, kelime arası boşluklar, kelime içi boşluklar vb. hataları normalize edilmesi gerekmektedir. Özellikle Osmanlıca metinlerde bitişmeyen harfler kelime içi boşluğa (zero width non-joiner) sebep olur. Bundan dolayı OCR ve alfabe çevirisi sırasında kelime içi boşluk ile kelime arası boşluk birbirine karıştırıldığında ortaya kelime bölütleme problemi çıkar. Bu problem alfabe çevirisi sırasında sıkça karşılaşılan bir problemdir.

Tablo 2: *OCR hata örnekleri*


دوردق. بلى اينجه ، چيزمهلرى طار و پارلاق ، قالپاغى چارپ*يق ،   ↓ ↑ ↕   طوردق. بلى ا*نجه ، چيزمهلرى طار و پارلاق ، قالپاغى چارپييق ،

3 Osmanlıca-Türkçe Alfabe Çevirisi

Alfabe çevirisi Osmanlı alfabesindeki Osmanlıca metnin Türk alfabesine metni değiştirmeden yani birebir bilgisayarlı ortografik alfabe çevirisidir. Burada her ne kadar birebir çeviri terimi kullanılsa da, Osmanlıcada genellikle sadece sessizler ve uzun sesliler yazıldığından bilgisayarlı alfabe çevirisi karmaşık bir işlem olup bildiğimiz kadarıyla şimdiye kadar kullanıma açık web tabanlı uygulaması olan sadece bir adet prototip çalışma mevcuttur [3]. Osmanlı ve Türk alfabesindeki sesli ve sessiz harfler arasında çoktan çoğa bir eşleşme söz konusudur. Ayrıca alfabe çevirisinin Türkçedeki imla ve gramer kuralları uygun şekilde yapılması gerekmektedir. Türkçede uzun seslilere ek olarak kısa sesliler de yazıldığından Osmanlıca ve Türkçe kelimeler arasında da çoktan çoğa eşleşme söz konusudur. Bu yüzden alfabe çevirisinde yüzeysel yapıbilimsel çözümleme, yapıbilimsel üretim, belirsizlik giderme, seslendirme (vowelization) vb. işlemlerin yapılması gerekmektedir.

Osmanlıca alfabesi 28 harfli Arap alfabesinin genişletilmiş bir çeşididir. 4 tane okutucu harf bulunmaktadır. Bu dört harf Türkçedeki 8 ünlü sese karşılık gelmektedir. Türkçe alfabesi 29 harften oluşmaktadır. 8 ünlü ve 21 ünsüz harften oluşur.

Osmanlıca-Türkçe Alfabe Çevirisi (i) Ortografik Alfabe Çevirisi, (ii) Kelime Bölütleme (iii) Yazım Düzeltme, (iv) Seslendirme, (v) Kelime tahmini ve (vi) İsim Tamlaması ve Birleşik kelimeler olmak üzere kabaca altı aşamadan gerçekleştirilir. Geliştirilen alfabe çevirisi sistemi bir örnek ile Şekil 2'de gösterilmiştir.

Şekil 2: Osmanlıca-Türkçe alfabe çeviri aracı

Birinci aşamada ortografik alfabe çevirisi aşaması olup bu aşamada Osmanlıca kelime gövdelenerek gövdeler ve ek-katarlarına ayrılır. Sonrasında Osmanlıca gövdeler ve ek-katarları gövde ve katar çeviri sözlükleri kullanılarak Türkçe gövdeler ve ek- katarlarına ulaşılır. Bir sonraki adımda Türkçe gövdeler ve ek katarları bitiştirilerek Osmanlıca kelimenin Türkçe karşılığı elde edilir. Bu şekilde çözümlenemeyen bir kelime olursa, bu kelimeler bir sonraki aşama olan kelime bölütleme aşamasına aktarılır. Kelime bölütleme aslında kelime bitişmesi (joined words) ve bölünmesi (segemented words) şeklinde iki problemden oluşmaktadır. Kelime bölütleme giderme algoritmasında şu an için pratik sebeplerden dolayı bir kelime bir önceki kelime ile birleştirilerek çözümlenmeye çalışılır. Eğer birleştirme sonucu geçerli bir kelime oluşursa, bu çözüm doğru kabul edilir. Eğer geçerli bir kelime oluşmazsa kelime bir sonraki aşama olan yazım düzeltmeye aşamasına aktarılır. Bu aşamada kelimede bir yazım hatası olduğu kabul edilerek yazım hatası düzeltme (spelling correction) algoritması uygulanır. Yazım düzeltme işlemi sonrası elde edilen kelime tekrar çözümlenmeye çalışılır. Çözümleme sonucu geçerli bir kelime elde edilirse bu çözüm doğru kabul edilir. Eğer kelime çözümlenmezse, söz konusu kelime bir sonraki aşama olan seslendirme (vowelization/vocalization) aşamasına aktarılır. Bu aşamada kelimenin sözlükte bulunmayan bir kelime (out of dictionary word) olduğu varsayımıyla kural tabanlı bir harf çevirisi algoritması uygulanır. Bu aşamada her zaman birçok çözüm elde edilir. Fakat çözümlerin doğrulanması mümkün değildir. Çünkü üretilen kelimeler sözlükte bulunmayan yabancı bir kelime ya da özel bir isim olabilir. Osmanlıca bir kelimenin Türkçede birden fazla karşılığı olabildiği için bir sonraki aşamada n-grams (dil modeli) kullanılarak çözümler arasından olasılığı en yüksek olan kelime seçilerek işlem tamamlanır. Bir sonraki aşamada metindeki isim tamlamaları ve bileşik isimler için geliştirilen algoritma ile isim tamlamaları ve bileşik isimler Türkçeye aktarılır ve böylece Türkçe metin oluşturulur.

Bu aşamaların bir örnek ile Tablo 3'de gösterilmiştir. Tabloda birden fazla çözüm { } sembolleri arasında verilmiştir. Kelime bölütleme aşamasında bölütlenmiş (اوقويه جق okuya+cak) kelimesi doğru şekilde çözümlenmiştir. Yazım düzeltme aşamasında حرايه → haraye kelimesi حرابه → harabe şeklinde düzeltilmiştir. Seslendirme aşamasında معمورة → mamure doğru biçimde elde edilmiştir. Osmanlıca kelimelerin Türkçede birden fazla okunuşu söz konusu olabilmektedir: بر →{bir, ber}, اولان →{ölen, olan, avlan} Bu durumda Türkçe karşılıkları n-grams ile doğru sıraya koymak gerekmektedir: بر →{bir, ber}, اولان →{olan, ölen, avlan} şeklinde sıralanmıştır. Tamlama ve Birleşik kelime aşamasında بلاد اسلاميه→ *bilad islamiyye* kelimesi *bilad-ı islamiyye* şeklinde düzeltilmektedir.

Tablo 3: *Osmanlıca-Türkçe alfabe çevirisi adımları*

Adım	*Sonuç*
Osmanlıca metin	ماضيده هر برى بر معمورة مدنيت اولان بلاد اسلاميه بوكون؛ قسوت انكيز برر خرايه حالنى المش. قواى طبيعيه ميدان اوقويه جق
Alfabe çevirisi	mazide her {berri, beri, biri} {bir, ber} معمورة {müdünüyet, medeniyet} {ölen, olan, avlan} bilâd islâmiyye {bugün, bükün} kasvet{enekyiz, engiz} birer حرايه halını {elmiş,almış}. kuva tabiyeye meydan اوقويه جق
Kelime bölütleme	mazide her {berri, beri, biri} {bir, ber} معمورة {müdünüyet, medeniyet} {ölen, olan, avlan} bilâd islâmiyye {bugün, bükün} kasvet {enekyiz, engiz} birer حرايه halını elmiş, almış}. kuva tabiyeye meydan okuyacak
Yazım düzeltme	mazide her {berri, beri, biri} {bir, ber} معمورة {müdünüyet, medeniyet} {ölen, olan, avlan} bilâd islâmiyye {bugün, bükün} kasvet {enekyiz, engiz} birer harabe halını {elmiş, almış}. kuva tabiyeye meydan okuyacak
Seslendirme	mazide her {berri, beri, biri} {bir, ber} mamure {müdünüyet, medeniyet} {ölen, olan, avlan} bilâd islâmiyye {bugün, bükün} kasvet {enekyiz, engiz} birer harabe halını {elmiş, almış}. Kuva tabiyeye meydan okuyacak
n-grams	mazide her {biri, berri, beri} {bir, ber} mamure { medeniyet, müdünüyet} {olan, ölen, avlan} bilâd islâmiyye {bugün, bükün} kasvet {enekyiz, engiz} birer harabe halını {elmiş, almış}. Kuva tabiyeye meydan okuyacak
Tamlama & Birleşik kelimeler	mazide her {berri, beri, biri} {bir, ber} mamure {müdünüyet, medeniyet} {ölen, olan, avlan} bilâd -ı islâmiyye {bugün, bükün} kasvet {enekyiz, engiz} birer harabe halını {elmiş, almış}. Kuva-ı tabiyeye meydan okuyacak

4 Osmanlıca-Türkçe Dil Çevirisi

Dil çevirisi Türk alfabesindeki Osmanlıca metnin bilgisayarlı çeviriyle Modern yani günümüz Türkçesine çevirisidir. Çeviri sonucu ortaya Türk Alfabesinde Modern Türkçe metin çıkar. Dil çevirisi doğal dil işlemenin en önemli ve en zor problemlerinden bir tanesidir. Ama Osmanlıca-Türkçe çeviri, aynı dilin farklı özellikler taşıyan iki farklı zaman dilimindeki sürümleri arası çeviri olduğundan farklı diller arası çeviriye göre daha basittir. Fakat bu çeviri söz dağarcığı, sözdizim ve anlamsal anormalliklerden dolayı yine de kolay bir problem değildir. Bu adımda kelime-grubu tabanlı birebir çeviri yaklaşımıyla ilerlenebileceği gibi, derin öğrenme kütüphaneleri kullanılarak cümle tabanlı makina çevirisi yaklaşımı da kullanılabilir. Çeviri öncesi (pre processing), sırası ve sonrasında (post processing) yüzeysel/tam yapıbilimsel ve/veya sözdizimsel çözümleme, üretim, belirsizlik giderme, kelime anlamı belirsizliği giderme, varlık ismi tanıma vb. işlemlerin yapılması gerekmektedir.

Osmanlıca - Türkçe dil çevirisi için kelime grubu tabanlı basit bir çeviri sistemi geliştirilmiştir. Bu yöntem dil içi çeviri için kullanılabilecek en basit yöntemlerden bir tanesidir. Yöntem kelime öbeği tabanlı ve mekanik olarak işleyen ve bir cümleyi öbek öbek soldan sağa doğru tarayarak Osmanlıcadan Modern Türkçeye aktaran bir yöntemdir. Bu yöntemin basit olmasına karşın çok karmaşık olmayan cümleler için etkin bir yöntem olduğunu düşünüyoruz ve elde edilen sonuçların daha ileri yöntemlerin geliştirilmesinde ve performans analizinde bir temel (baseline) olarak ta kullanılabileceği kanaatindeyiz. Osmanlıca Türkçe bir çeviri örneği **Şekil 3**'te verilmiştir.

Şekil 3: Osmanlıca-Türkçe dil çeviri aracı

Problemin zorluğuna dikkat çekmek amacıyla Osmanlıca Türkçe dil çevirisinde bazı problem ve zorlukları örnekleriyle aşağıda paylaşılmıştır. Bu örnekler hem veri setinin hem de çeviri algoritmasının geliştirilmesi ve iyileştirilmesinde yönlendirici değere sahiptir.

1. *Yazılışı aynı kelimeler*: Osmanlıca ve Modern Türkçedeki ortak ve yaygın kelimeler çeviriye sokulmadan doğrudan aktarılmalıdır. "bir" gibi Osmanlıcada *kuyu* anlamına da gelen bazı kelimeler yanlış çeviriye sebep olabilmektedir.
2. Osmanlıcada bazı metinlerde anlatım ağdalı ve karmaşık olduğunda çeviri zorlaşmaktadır. Aşağıdaki örnekler bu tür örneklerdir:

   Makūle mesâil-i hilâfiyyeyi pâ-bend-i ahmakān
   Niçe kīl ü kāl ve bahs ü cidâle müeddî oldu.
   Fenn-i kitâbet ü hesâb ü siyâkate müteallik müşkil
   Reca'nâ mine'l-cihâdi'l-asgar ile'l cihâdi'l-ekber (Arapça)

3. *Ayrı yazılan ekler*: Osmanlıca ve Türkçe bazı anlatım farklılıkları birebir çeviride ifade bozukluğuna sebep olabilmektedir. Örneğin Türkçe geçmiş zaman -dH eki Osmanlıcada "idi" olarak ayrı yazılmaktadır. Örneğin *ehl idi* metni *yetenekli idi* yerine *yetenekliydi* diye çevrilmelidir.
4. *Bitişik yazılan ekler*: Normalde ayrı yazılması gerekirken birleşik yazılan ekler sözlükte arama ve eşleştirme yapmayı güçleştirmektedir. Örneğin makūle mesâil-i hilâfiyyeyi pâ-bend-i ahmakā ifadesindeki *hilâfiyyeyi* kelimesindeki *-i* ekinin *hilâfiyye-i* şeklinde ayrı yazılması gerekmektedir.
5. *Harf ikilemesi*: Türkçe olmayan bazı kelimelerdeki harf ikilemeleri Türk alfabesine aktarılırken bazen korunmakta bazen de tekilleştirilerek yazılmaktadır. Örneğin *hilâfiyyeyi* kelimesi *hilâfiyeyi* şeklinde de yazılabilmektedir.
6. *Küçük büyük harf ayırımı*: Osmanlıcada küçük büyük harf ayrımı olmadığından özel isimlerin bulunması ve çevriminde problem yaşamaktadır. Örneğin *Selimiye* kelimesinin *sağlamıye* diye çevrilmesi yada *murad rabi*'nin *istek dört* gibi çevrimi söz konusu olabilir.

7. *Çoklu morfolojik çözüme sahip kelimeler:* Bir kelimenin birden fazla morfolojik çözümü yani birden fazla gövdesi söz konusu olduğunda şu an için kullandığımız *en uzun gövde en kısa ek katarı* yöntemi morfolojide yetersiz kalmaktadır. Örneğin Osmanlıca *al* kelimesi *almak* ya da *aile* olarak Türkçeye aktarılabilir. Burada doğru karşılığı bulmak için çeviri sonrası dil modelleri (n-grams) kullanılarak doğru çözüme ulaşılabilir. Benzer örnekler:
   - şehr → şehir (isim), ay (isim)
   - bak → bak (fiil), korku (isim)
   - azm → gayret (isim), kemik (isim)
8. *Çoklu yüzeye sahip kelimeler*: Osmanlıcadaki birçok kelimenin birden fazla imlası (yazım şekli, yüzey, surface) olması sözlüğün hazırlanmasını ve çeviriyi güçleştirmektedir. Kelimelerin farklı yüzeylerinin sözlüğe işlenmesi ya da sözlükte arama yaparken kelime benzerliği üzerinde arama yapmak gerekebilir. Örneğin yukarıda *azm* kelimesinin *azim* olarak *elh* kelimesinin *elih* olarak yazımları daha yaygın kullanılmaktadır. Osmanlıcanın Türk alfabesiyle yazımında ayırıcı ya da düzeltme işaretleri denen diakritiklerin metinde doğru ve standart bir şekilde kullanımı çeviride çok önemlidir. *Reca'nâ mine'l-cihâdi'l-asgar ile'lcihâdi'l-ekber* örneğinde olduğu gibi kesme işareti (apostrof), kısa çizgi (tire) ve şapka gibi işaretler metin ön işlemesi ve normalizasyonunda ve sözlük geliştirmede dikkat edilmesi gereken konulardır. Örneğin *bû* kelimesinin Türkçedeki karşılığı *koku* kelimesidir. Çeviri uygulamasına verilen bir metinde bu kelimenin şapkasız yazılması durumunda Türkçeye işaret sıfatı ya da zamiri olarak yanlış çevrilmesi söz konusu olacaktır.
9. *Farklı dilden alıntılar*: Metin içerisinde özellikle Arapça ve Farsça alıntılar Osmanlıca ile karıştırılabilmekte ve Osmanlıca zannedilebilmektedir. *Reca'nâ mine'l-cihâdi'l-asgar ile'l cihâdi'l-ekber* örneğinde olduğu gibi Arapça, Farsça ve Osmanlıca çok sayıda ortak kelimeye sahip olduğu için yabancı dildeki alıntıları ana metinden ayırt etmek için yapılacak bir dil tanıma (language detection/recognition) işlemi zorlaşmaktadır. Bu örnekteki metin tamamen Arapça olmasına rağmen *cihad*, *ekber* ve *asgar* kelimeleri aynı zamanda Osmanlıca kelimelerdir.

5 Sonuçlar

Bu çalışmada Osmanlıca dokümanların *OCR, alfabe çevirisi* ve *dil çevirisi* olmak üzere bir uçtan diğer uca yani Osmanlıca dokümandan Modern Türkçe metne üç adımda otomatik olarak çevrilmesi amaçlanmaktadır. OCR ile Osmanlıca dokümanların görüntü dosyaları düzenlenebilir metine dönüştürülmekte, alfabe çevirisiyle Osmanlıca metin Arap-tabanlı Osmanlı alfabesinden Latin-tabanlı Türk alfabesine aktarılmakta ve dil çevirisiyle Türk alfabesindeki Osmanlıca metin Modern Türkçeye çevrilmektedir.

Çalışmanın birinci amacı Osmanlıcadan Türkçeye aktarım sürecini tüm yönleriyle ortaya koymak ve bu süreçte karşılaşılan problemlerin tanımlayıp onlara yönelik olası çözümleri yakından incelemektir. Çalışmanın ikinci amacı aktarımın her üç adımına yönelik çevrimiçi araçlar geliştirmek, bu araçları benzer bilimsel ve ticari araçlarla karşılaştırarak test etmek ve sonrasında kullanıma açmaktır. Çalışmanın üçüncü amacı geleceğe yönelik bir hedeftir. Gelecekte her adım için ayrı ayrı geliştirilen araçların bir arada daha etkin çalışabilmesi ve aktarım sürecinin toplam performansının iyileştirilmesine yönelik çalışmalar yapılacaktır. Derin sinir ağları büyük veri setleri eğitilerek daha önce çözümü zor olan problemlere yönelik başarılı çalışmalar yapılabilmektedir. Örneğin bir adımda elde edilen veriler bir önceki adıma geri beslenerek o adımın iyileştirilmesi söz konusu olabilmektedir. Ya da ardışık iki adım birleştirilerek bir arada çözümlenebilecektir. Örneğin ORC adımı atlanarak -diğer bir deyişle bir sonraki adımla birleştirilerek- doküman görüntüsünden doğrudan Türk alfabesine dönüşüm yapılabilir. Veya alfabe çevirisi atlanarak, Osmanlıca metinden günümüz Türkçesine doğrudan çeviri yapılabilir. Hatta Osmanlıca doküman görüntüsünden günümüz Türkçesine direkt çeviri söz konusu olabilir.

Osmanlıca dokümanların Modern Türkçeye aktarımı toplumumuzun teknoloji ile çözülmesi gereken önemli kültürel ve bilimsel problemleri arasında yer almaktadır. Bilimsel veya ticari, şimdiye kadar yapılan çalışmalarda geliştirilen OCR araçları sayıca az olup elde edilen doğruluk oranları düşük olduğu için ihtiyaca cevap verecek durumda değildir. Üzerinde en çok ve en uzun süre çalışılan problemlerden biri olan Osmanlıca OCR konusunda geliştirilen araçlar, Abby FineRader veya Google Docs gibi kapalı kodlu ticari OCR araçlarının veya Tesseract gibi açık kodlu ürünlerin performansının altında kalmaktadır. Bu çalışmada geliştirdiğimiz OCR aracı hem Google Docs hem FineReader hem de Tesseract'tan daha yüksek doğruluk oranı (%96) vermektedir.

Osmanlıca-Türkçe alfabe çevirisi konusu şimdiye kadar daha çok dilcilerin ilgilendiği bir problem olarak kalmışsa da son zamanlarda doğal dil ve makine öğrenmesi konularındaki gelişmelere paralel olarak bu konuya yönelik bir elin parmakları kadar az sayıda çalışma yapılmıştır. Bu çalışmalarda kullanıma açık tek araç bizim geliştirdiğimiz alfabe çevirisi aracıdır. Yapılan testlerde bu aracın doğruluk oranı %98 olarak belirlenmiştir.

Osmanlıca-Modern Türkçe dil çevirisi konusunda ise çok daha az sayıda çalışma yapılmış olup bizim geliştirdiğimiz araç hariç henüz ortaya elle tutulur bir model ya da araç geliştirilememiştir. Oysa batı dillerinde çeviri konusunda başarılı birçok çalışma mevcut olup günlük hayata girmiş araçlar ortaya çıkmıştır.

6 Beyanname

6.1 Çalışma Sınırlamaları

Yazarlar, bu çalışmada araştırma sonucunu önemli ölçüde etkileyebilecek herhangi bir sınırlama ile karşılaşmadığını beyan eder.

6.2 Teşekkür

Yazarlar, bu çalışmanın kalitesini artıran yapıcı öneriler için anonim hakemlere teşekkürlerini sunar.

6.3 Finansman Kaynağı

Yazar(lar) herhangi bir fon kaynağı beyan etmemiştir.

6.4 Rakip Çıkarlar

Bu çalışmada herhangi bir çıkar çatışması yoktur.

6.5 Yazarların Katkıları

Sorumlu Yazar; İshak DÖLEK: Makaledeki çalışmayı bir doktora tezi olarak yapmak, sunulan araçlara ait algoritmaları ve örnekleri hazırlamak, yorumlamak ve anlatmak, geliştirilen araçların ara yüzlerini sunmak, test sonuçlarını paylaşmak, makalenin temel çatısını oluşturup Giriş ve Sonuçlar bölümü hariç makaleyi yazmak.
2. Atakan KURT: Makalede sunulan doktora tezini yönetmek, Giriş ve Sonuçlar bölümlerini yazmak, makalenin tamamı üzerinde yorum, düzenleme ve düzeltmeler yapmak.

7 İnsan ve Hayvanlarla İlgili Çalışma

Bu tür bir çalışma için resmi onay gerekli değildir

7.1 Etik Onay

Bu çalışma bir masa başı incelemesi içerdiğinden, yazarlar tüm prosedürlerin ilgili kurumsal komitelerin etik standartlarına uygun olduğunu iddia etmektedir. Bu tür bir çalışma için resmi onay gerekli değildir.

7.2 Bilgilendirilmiş Onay

Çalışmaya dâhil edilen tüm bireysel katılımcılardan bilgilendirilmiş onam alınmıştır

Kaynakça

[1] M. Ergin, "Osmanlıca Dersleri", *İstanbul: Boğaziçi yayınları*, 2020.

[2] S. Kirmizialtin ve D. Wrisley, "Automated Transcription of Non-Latin Script Periodicals: A Case Study in the Ottoman Turkish Print", *Archive arXiv preprint arXiv:2011.01139,* 2020. https://arxiv.org/abs/2011.01139

[3] M. Mohd, F. Qamar, I. Al-Sheikh and R. Salah, "Quranic Optical Text Recognition Using Deep Learning Models", *IEEE Access*, vol. 9, pp. 38318-38330, 2021, doi: 10.1109/ACCESS.2021.3064019.

[4] Miletos OCR [Çevrimiçi]. Erişim: www.miletos.com

[5] IRCICA [Çevrimiçi]. Erişim: library.ircica.org.

[6] I. Dolek and A. Kurt, "Ottoman OCR: Printed Naskh Font," *2021 International Conference on INnovations in Intelligent SysTems and Applications (INISTA)*, 2021, pp. 1-5, doi: 10.1109/INISTA52262.2021.9548616.

[7] A. Kurt, and E. F. Bilgin. "The Outline of an Ottoman-to-Turkish Automatic Machine Transliteration System" *First Workshop on Language Resources and Technologies for Turkic Languages.* 2012.

[8] J. Korkut, "Morphology and Lexicon-Based Machine Translation of Ottoman Turkish to Modern Turkish", *Princeton University, Princeton, NJ, USA*, 2019.

[9] A. A. Jaf, S. K. Kayhan, "Machine-Based Transliterate of Ottoman to Latin-Based Script", *Scientific Programming*, vol. 2021, Article ID 7152935, 8 pages, 2021. https://doi.org/10.1155/2021/7152935

[10] E. Özkan and G. Ercan, "Modernization of old turkish texts,", *26th Signal Processing and Communications Applications Conference (SIU)*, 2018, pp. 1-4, doi: 10.1109/SIU.2018.8404308.

[11] J. Memon, M. Sami, R. A. Khan and M. Uddin, "Handwritten Optical Character Recognition (OCR): A Comprehensive Systematic Literature Review (SLR)," *in IEEE Access*, vol. 8, pp. 142642-142668, 2020, doi: 10.1109/ACCESS.2020.3012542.

Research Article
Journal of Smart Systems Research (JOINSSR) 3(1), 11-21, 2022
Recieved: 17-March-2022 Accepted: 15-April-2022

SAKARYA UNIVERSITY OF APPLIED SCIENCES

Effect of Temperature on Pack Siliconizing of Ti6Al4V Alloy

1st Eşref Furkan TEPE , 2nd Tuba YENER , 3rd Gözde Fatma EFE*

[1] Metallurgy and Materials Engineering, Faculty of Technology, Sakarya University of Applied Sciences, efurkantepe@gmail.com,

[2,] Metallurgy and Materials Engineering, Engineering Faculty, Sakarya University, tcerezci@sakarya.edu.tr,

[3] Metallurgy and Materials Engineering, Faculty of Technology, Sakarya University of Applied Sciences, gcelebi@subu.edu.tr,

ABSTRACT

This study aims to investigate the temperature effects on silicide coating formed by pack siliconizing method on Ti6Al4V substrate. Pack siliconizing process was conducted out for 2h at 1000°C, 1100°C, 1200°C, in vacuum atmosphere, by using Si as Si source, Al_2O_3 powder as filler and NH_4Cl as an activator. The presence of the formed phases such as Ti_5Si_3, TiSi, $TiSi_2$ on coating, and non-stoichiometric Al_20_3 compound from the pack mixture was actualized by X-ray diffraction analysis (XRD). It was observed that the silicide coating on Ti6Al4V substrate is compact, dense and the coating thickness varies between 10.5-30.4 µm depending on the treatment temperature. The morphological features of the coating and dispersion of the elements in the silicide layer was examined by using electron microscope (SEM) and elemental analysis (EDS). Hardness of silicide layer measured by Vickers method and determined that the hardness ranges between 1170 $Hv_{0,025}$ to 1450 $HV_{0,025}$.

Keywords: Pack cementation, surface modification, silicide coating, intermetallic coating.

1 Introduction

In the last century, pure titanium and its alloys have been attracting both industrial and academic attention due to its superior properties such as good strength weight ratio, high ductility, good biocompatibility, high corrosion resistance [1]. While pure titanium can easily match desired design properties for low strength applications , for higher strength applications and more severe conditions, titanium alloys can perform better [2]. Accordingly, major titanium alloys such as Ti6Al4V, Ti-5Al-2.5Sn, Ti8Al-1Mo-1V, Ti6Al-2Sn-4Zr-2Mo, Ti6Al-2Sn-4Zr-Mo, Ti-8Mo-8V-2Fe-3Al have been used in higher technology applications in aerospace, biomedical, automotive industry. Even tough, titanium alloys exhibits challenging corrosion resistance until 550°C in engineering applications, due to $Ti0_2$ formation then surface would be prone to hot corrosion failure [3]. Therefore, material scientists have focused on surface modifications in order to improve both hot corrosion resistance and wear resistance. Many surface modifications such as CVD, PVD, thermal spray coatings, ion implantation, pack cementation method developed to answer this need [4–7]. Among these methods, pack cementation is known to be one of the

* Corresponding Author's email: gcelebi@subu.edu.tr

most economic and capable of producing smooth and uniform final surface properties.

The most common pack cementation applications are aluminizing, chromizing, siliconizing in which source of coating material is aluminum, chrome, silicon respectively. These pack cementation methods are mainly used in aerospace and automotive engines as hot oxidation and wear resistant coatings. Comparing to the other coatings, which are used in hot engine sections of aerospace and automotive systems, such as thermal barrier coatings and CVD coatings, pack cementation methods appear to be one of the most cost-effective solutions for serial production. On the other hand, processs flow is much more easy and doable than other refractory coatings, even tough some scientists call pack cementation method as in-situ CVD due to its similarity in the process [6]. In previous papers, it can be noticed that mainly the focus has been on pack aluminizing and chromizing rather than siliconizing [8,9]. Nevertheless, in some aspects, pack siliconizing is more promising application for high temperature environments where the substrate can be exposed to high temperature oxidation and wear. Since coating would made of hard and stable intermetallic titanium silicides such as Ti_5Si_3, $TiSi_2$, TiSi, it can bear excessive temperatures up to 2000°C without substrate being effected by heat [10]. These properties may aid titanium to be used in applications that normally it cannot be used by its own nature. Authors aim to contribute to the literature by applying pack siliconizing on Ti6Al4V alloy in optimum process period of 2 hours for different temperatures of 1000°C, 1100°C and 1200°C in order to understand the formation morphology, temperature-time correlation on layer growth and the mechanical properties.

2 Experimental Procedure

Ti6Al4V plates to be coated, were cut into 20x20x2 mm square shape. Since titanium is very active metal, substrate plate surfaces have been grinded with 120, 240, 320, 600, 800, 1000, 1200 grit sand paper before pack process in order to remove either oxides or impurities on surface.

Pack has been prepeared with the stoichiometrically arranged powder mixtures of NaH_4Cl as activator, pure silicon as silicon source and Al_20_3 as reactive. Surface grinded samples were embedded into the pack mixture in an alumina crucible and covered with graphite to prevent oxygen diffusion to system as shown in Figure 1.

Pack siliconizing process was performed in vacuum atmospheric furnace with argon gas to prevent oxidation at the temperatures of 1000, 1100 and 1200°C for 2 hours and cooled in the furnace till to room temperature. After siliconizing process cross-sections of surface coated samples were prepared metallographically for microstructural studies.

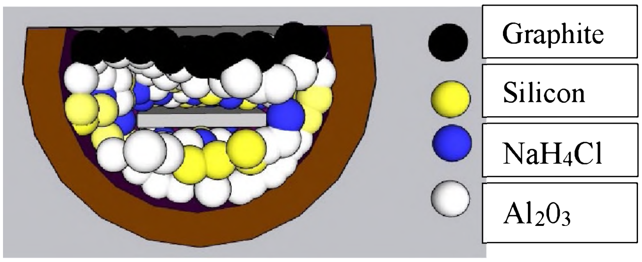
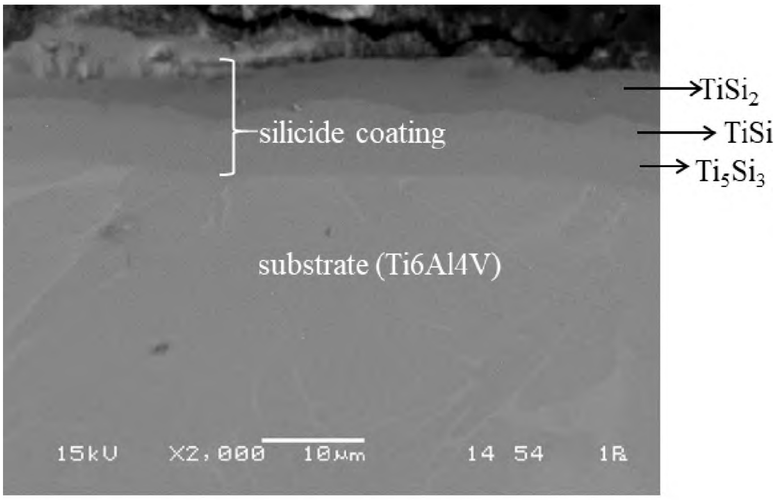


Figure 1 Schematic illustration of pack mixture for pack siliconizing process of Ti6Al4V

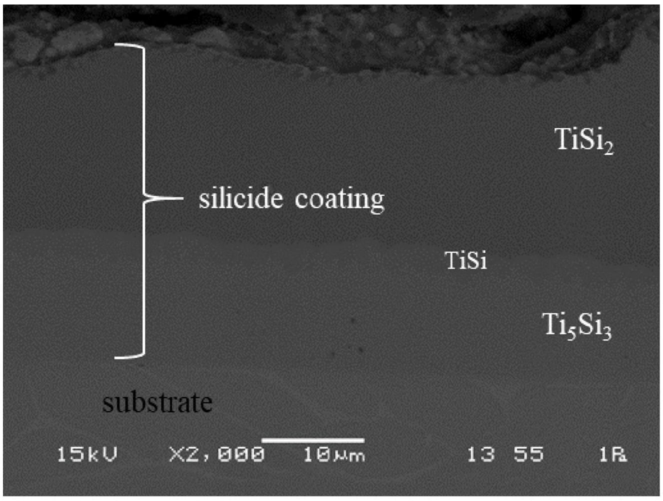
Microstructure examination of siliconized Ti6Al4V specimens were performed by JOEL JSM-5600 model scanning electron microscope (SEM). Microhardness tests were conducted out by EMCOTEST DUROSCAN-70 to understand mechanical properties of the Silicide layers (Vickers Hv0.025). The dominant phases, formed on the coating were identified by Rigaku X-ray diffractometer using CuKα radiation with 1,54056 A° wave length and 2 θ angle selected between 20° and 90°.

3 Results and Discussion

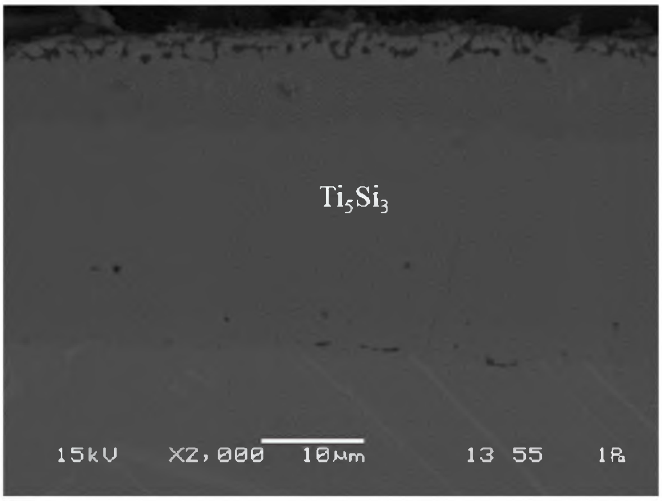
According to SEM examination given in Figure 2, it can be clearly noticed that formed coating surface has smooth morphology. In section-cut samples siliconized at 1000 and 1100°C there are mainly four obvious layers (Fig.2a, b). Based on XRD analysis, these layers are TiSi, $TiSi_2$, Ti_5Si_3 phases and the matrix (Fig. 3). On the other hand, EDS analysis revealed that Si concentration is more intense in outer layer than inner layers, shows that the first formed layer is $TiSi_2$ and turned into TiSi and Ti_5Si_3 with increasing treatment temperature (Fig. 4).



a)



b)



c)

Figure 2. SEM morphologies of Ti6Al4V alloy pack siliconized at a) 1000°C, b) 1100°C and c) 1200°C for 2 hours.

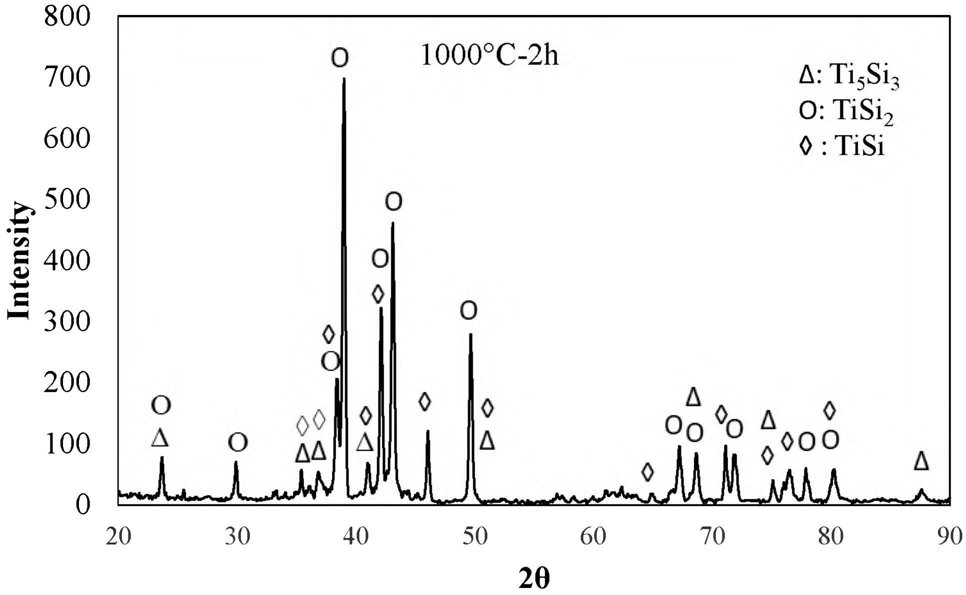
The reactions in the pack are basically so similar to CVD coating processes. Primarily, the reactions begin with the dissociation of the activator NH4Cl into NH_3 and HCl in temperatures more than 340°C (1). Secondly, HCl reacts with Si to form gaseous $SiCl_4$ (2). As gaseous SiCl4 contacts titanium substrate, the reaction between Ti and $SiCl_4$ leads into atomic Si formation in order to further solid state diffusion occurs on surface so that TiSi intermetallic multilayer coating forms (3) [11].

$NH_4Cl(s)=NH_3(g)+HCl(g)$ (1)

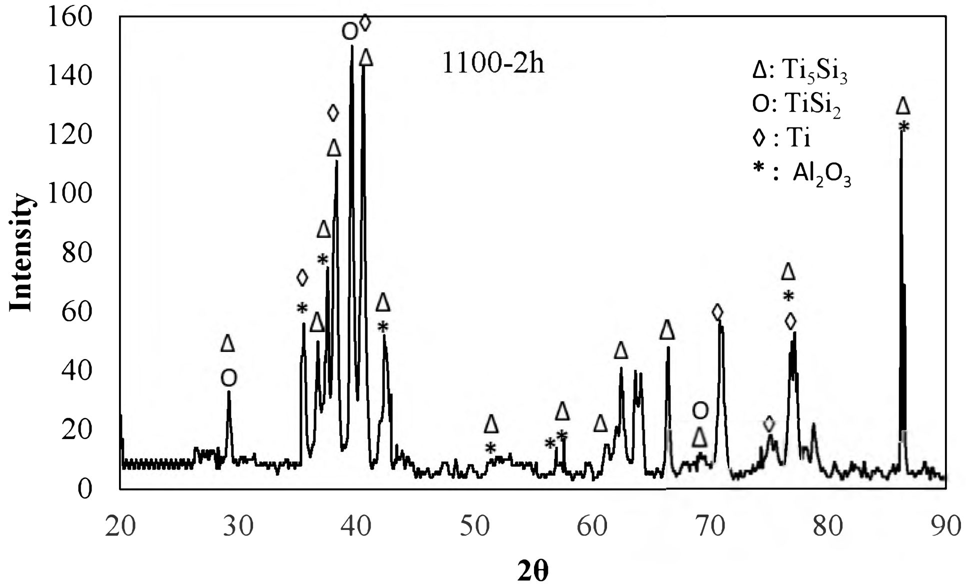
$4HCl+Si=SiCl_4(g)+2H_2$ (2)

$Ti+2SiCl_4+4H_2=TiSi_2+8HCl$ (3)

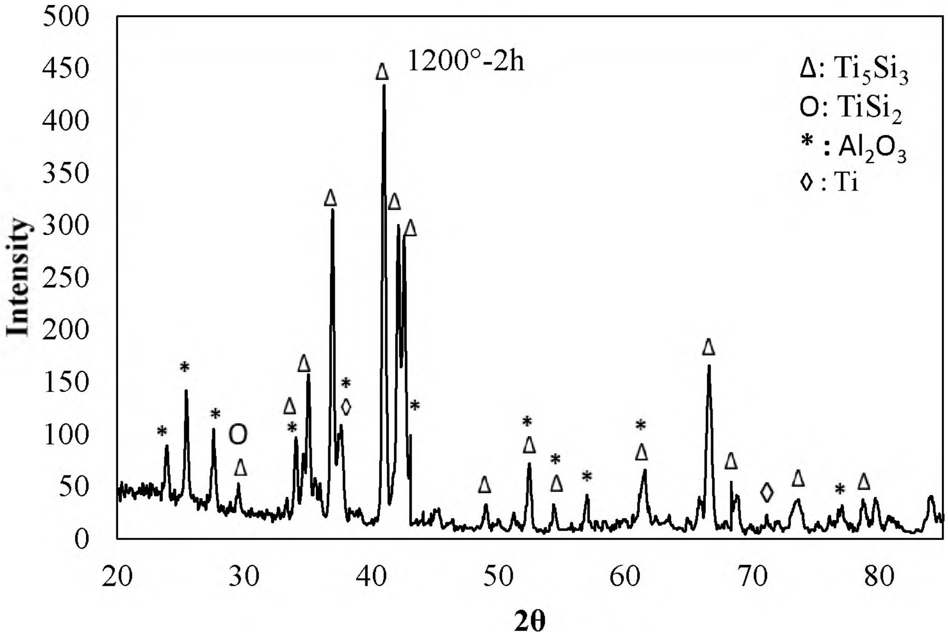
The coatings morphology is smooth and consist of multilayers as well as small amount of micro voids can be observed. The main reason why these voids form is that actually Kirkendall effect applies to the coating. Due to the difference of the mobility rates in diffusion couples such as aluminum-titanium in substrate matrix and silicon-titanium in coating, Kirkendall voids are likely to form in the system as in the process, silicon atoms move inwards meanwhile titanium atoms move outwards to form diffusion coating [12].


1000°C-2h
Δ: Ti5Si3
O: TiSi2
◊ : TiSi
Intensity
2θ

a)


1100-2h
Δ: Ti5Si3
O: TiSi2
◊ : Ti
* : Al2O3
Intensity
2θ

b)



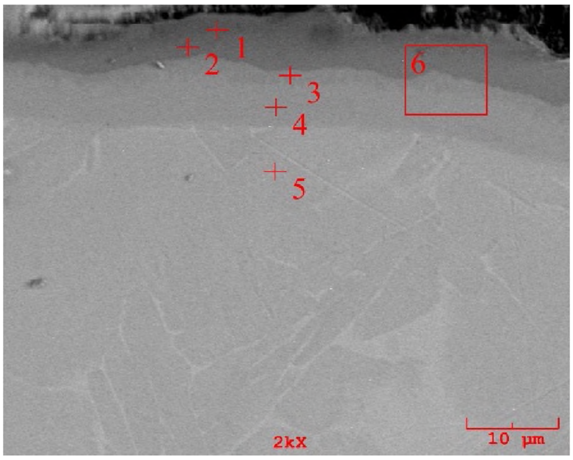
c)

Figure 3. XRD analysis of Ti6Al4V alloy pack siliconized at a) 1000°C, b) 1100°C and c) 1200°C for 2 hours.

As known from the previous works, thermochemical coatings such as chromizing, aluminizing, siliconizing etc. the layer composition and growth behaviours can be affected from both the substrate compositions and pack composition [13]. Since the siliconizing process driven by solid state diffusion, in order to understand the growth behaviour, it is highly important to understand the diffusion phenomena [14]. In diffusion coatings usually Arhenius equation applies and coating growth expected to be parabolic as function of time and temperature. It is highly mentioned that as temperature and time raises, the coating would be thicker. The equation is:

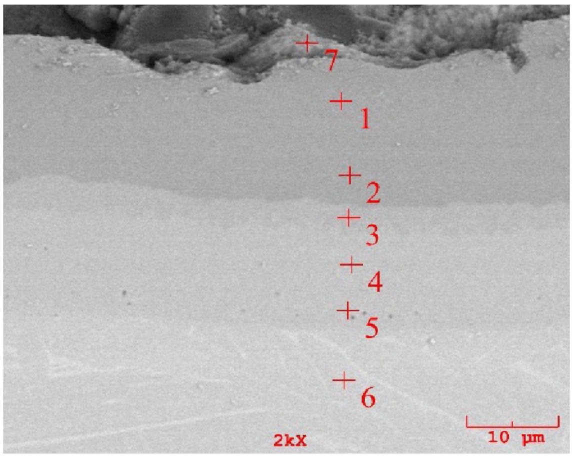
L2 = KP×t

where L is layer thickness, KP is parabolic rate constant and t is siliconizing time [15].



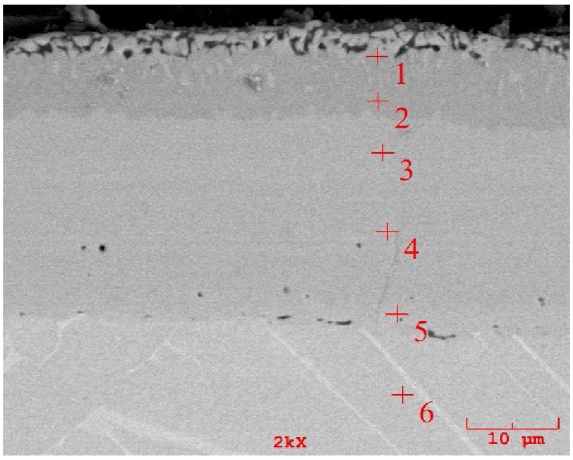
Marks	Elements, Conc. %				
	O	Al	Si	Ti	V
1	0.000	30.90	42.65	25.18	1.257
2	0.000	5.82	59.13	33.76	1.27
3	1.498	0.159	47.24	49.93	1.158
4	2.332	0.350	40.32	56.18	0.810
5	2.169	12.618	0.749	81.717	2.747
6	0.000	0.125	50.50	47.69	1.669

a)



Marks	Elements, Conc. %				
	O	Al	Si	Ti	V
1	1.783	0.268	59.69	38.25	0.000
2	1.450	0.238	60.46	36.26	1.575
3	2.229	0.138	42.909	53.256	1.468
4	1.657	0.288	38.09	58.46	1.494
5	1.423	0.086	37.22	59.09	2.178
6	1.046	9.991	1.329	85.80	1.825
7	4.013	1.766	59.37	34.84	0.000

b)



Marks	Elements, Conc. %				
	O	Al	Si	Ti	V
1	2.044	1.808	37.973	57.269	0.90
2	0.359	0.307	42.670	56.417	0.24
3	2.217	0.068	37.409	59.501	0.80
4	0.572	0.266	38.408	59.006	1.74
5	0.557	1.255	29.709	67.326	1.15
6	0.273	8.942	1.049	87.981	1.75

c)

Figure 4. SEM- EDS analysis of Ti6Al4V alloy pack siliconized at a) 1000°C, b) 1100°C and c) 1200°C for 2 hours.

The coating thicknesses respectively measured through SEM and were obtained 10.5, 27.45, 30.4 µm as result and given in the Figure 5. As temperature raised, the thicker coating layer has been obtained. It is seen that increasing temperature made the diffusion easer and the coating layer has grown parabolically similar to study done by Cotell et al [16].

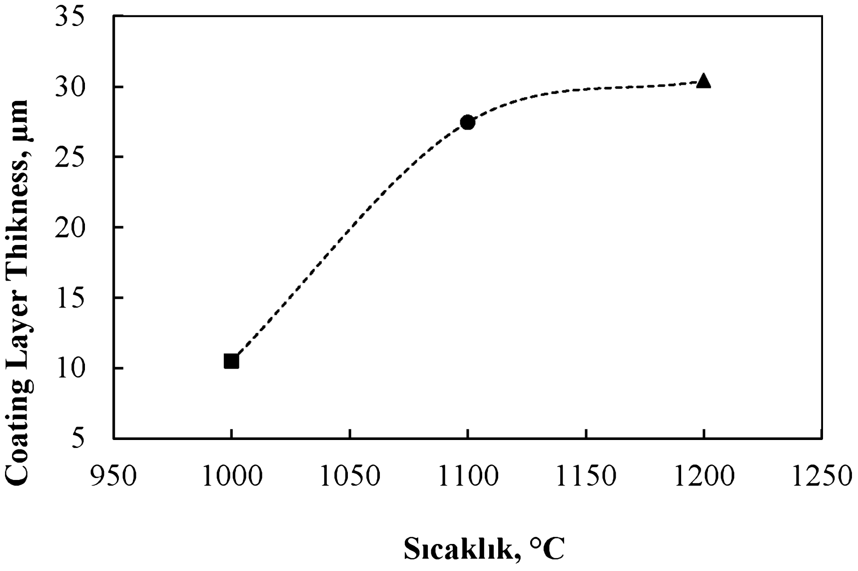


Figure 5. Variation of coating layer thickness of pack siliconized Ti6Al4V alloy versus treatment temperature.

By taking low silicon solubility in α-titanium into consideration, it can be revealed that β-titanium and silicon deposit, initiates a solid state reaction. Primarily, silicon diffuses into the substrate until it reaches to the critical point where titanium rich Ti3Si silicide begins to precipitate in Ti/Si interface near to substrate [17]. The solid-state reactions between substrate and silicon transforms into multilayer compact coating consist of various Ti_XSi_Y phases. Also, in another word, titanium has rather low mobility so that the first layer of the coating expectedly becomes titanium rich layer consist of equilibrium Ti_5Si_3 or Ti_2Si phases and then silicon rich phases such as TiSi, $TiSi_2$ will be formed according to TiSi phase diagram.

The obtained results indicate that the diffusion through the Ti_5Si_3 phase detected by XRD nevertheless some other titanium silicides are expected to present, but since their volume fractions are smaller than the detection limit of XRD, they could not be detected.

Above mentioned all diffusion-based reactions continues until all silicon source is ran out in the system. It can be also noted that in greater temperatures the number of layers significantly reduces.[18] The authors thinks that the underlying reason of this case is that the more temperature leads into the more interdiffusion between each layer.

The intermetallic multilayer coating mainly consist of Ti_5Si_3, Ti_2Si, TiSi, $TiSi_2$ phases is relatively almost 4 times harder than substrate Ti6Al4V material. While the substrate hardness was tested around 420 $HV_{0,025}$ the coating layer could reach up to 1450 $HV_{0,025}$. Hard coating layer exhibits hardness similar to TiN layers and it is highly wear resistant by its structure. It is also important to point it out that, coatings of the greater pack siliconizing temperatures, the harder both coating and substrate material became.

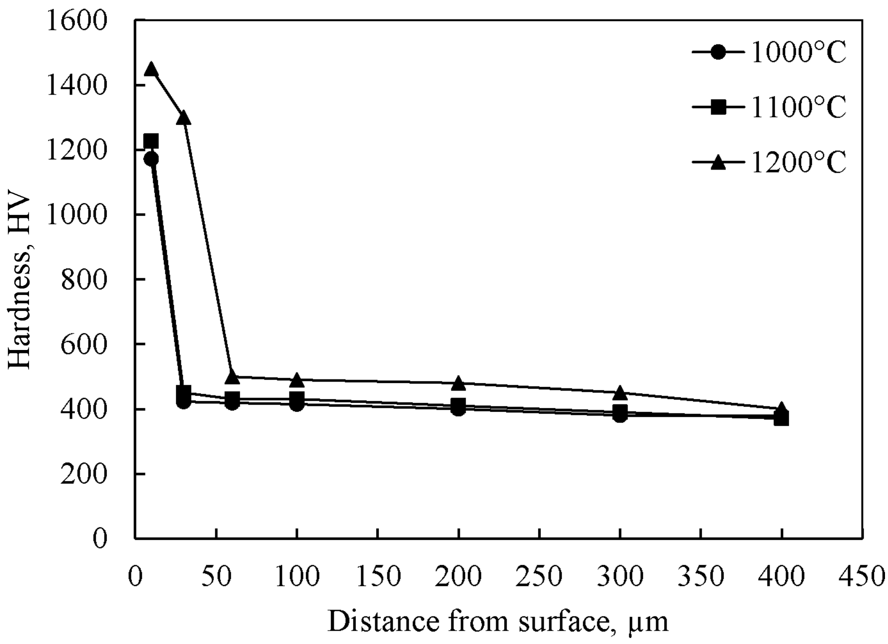


Figure 6. Microhardness distribution of silicide layer formed on Ti6Al4V alloy surface versus distance from the surface for 1000°C, 1100°C, 1200°C

4 Conclusions

In the present study following conclusions can be made:

1. The intermetallic compact silicide layers formed on Ti6Al4V are almost uniform and smooth.

2. There is a good bonding between the coating layers with the substrate material without any debonding.

3. The thickness of coating layer ranged from 10.5 to 30.4μm with increasing process temperature.

4. The coating layers confirmed by XRD and SEM analysis consists of multi phases such as $Ti5Si_3$, Ti_2Si TiSi and $TiSi_2$.

5. It was founded that the coating hardness increases for the coatings formed in higher temperatures and the hardness values ranges between 1170 $Hv_{0,025}$ to 1450 $HV_{0,025}$

6. It is concluded that process is highly depended on temperature. The coating layer grows almost parabolic and Arhenius law applied.

5 Declarations

5.1 Acknowledgements

The authors take this opportunity to acknowledge the financial support of Sakarya Applied Sciences University Scientific Research Projects Coordination (BAPK, Grant Number: 2021-50-01-063). Also special thanks to Ebru Yılmaz for her contribution during the laboratory activities and to Sakarya

University of Applied Sciences, Faculty of Technology, Metallurgical and Materials Engineering Laboratory where the experimental studies carried out.

5.2 Funding source

No funding source.

5.3 Competing Interests

There is no conflict of interest in this study.

5.4 Authors' Contributions

1. Eşref Furkan TEPE: Contribution to the article. (Performing experimental study, organizing and reporting the data, taking responsibility for the literature review during the research, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review during the research.)

2. Tuba YENER:, Contribution to the article. (Taking responsibility for the creation of the entire manuscript or the main part organizing and reporting the data reworking not only in terms of spelling and grammar but also intellectual content or other contributions.)

3. Corresponding Author Gözde ÇELEBİ EFE: Contribution to the article. (Developing ideas for the research, planning the materials and methods to reach the results, taking responsibility for the experiments, taking responsibility for the explanation and presentation of the results, taking responsibility for the creation of the entire manuscript or the main part.)

References

[1] M. Jackson, R.R. Boyer, Titanium and its Alloys: Processing, Fabrication and Mechanical Performance, Encycl. Aerosp. Eng. (2010) 1–16. https://doi.org/10.1002/9780470686652.eae199.

[2] R. Boyer, G. Welsch, E.W. Collings, Materials properties handbook : titanium alloys, 1994.

[3] K. Chou, P.W. Chu, E.A. Marquis, Early oxidation behavior of Si-coated titanium, Corros. Sci. 140 (2018) 297–306. https://doi.org/10.1016/j.corsci.2018.05.035.

[4] M. Hetmańczyk, L. Swadźba, B. Mendala, Advanced materials and protective coatings in aero-engines application co-operating with Manufacturing and processing, 2007. www.journalamme.org.

[5] F.J. Pérez, M.P. Hierro, M.C. Carpintero, F.J. Bolivar, Aluminum and silicon co-deposition by the chemical vapor deposition in fluidized bed reactor technique as a precursor of protective coatings of mullite, Surf. Coatings Technol. 184 (2004) 361–369. https://doi.org/10.1016/j.surfcoat.2003.11.001.

[6] R. Bianco, R.A. Rapp, Pack cementation diffusion coatings, Metall. Ceram. Prot. Coatings. (1996) 236–260. https://doi.org/10.1007/978-94-009-1501-5_9.

[7] T.R. Rautray, R. Narayanan, T. Kwon, K. Kim, Surface Modification of Titanium and Titanium Alloys by Ion Implantation Review Surface Modification of Titanium and Titanium Alloys by Ion Implantation, (2010). https://doi.org/10.1002/jbm.b.31596.

[8] A.R. Castle, D.R. Gabe, Chromium diffusion coatings The application of diffusion coatings has become, 1999.

[9] W. Yang, J. Park, K. Choi, C.H. Chung, J. Lee, J. Zhu, F. Zhang, J.S. Park, Evaluation of growth kinetics of aluminide coating layers on Ti-6Al-4V alloys by pack cementation and the oxidation behaviours of the coated Ti-6Al-4V alloys, Int. J. Refract. Met. Hard Mater. 101 (2021) 105642. https://doi.org/10.1016/j.ijrmhm.2021.105642.

[10] D. Vojtěch, B. Bártová, T. Kubatík, High temperature oxidation of titanium-silicon alloys, Mater. Sci. Eng. A. 361 (2003) 50–57. https://doi.org/10.1016/S0921-5093(03)00564-1.

[11] G.Ç. Efe, İ. Altınsoy, T. Yener, M. İpek, C. Bindal, S. Zeytin, Surface Modifi cation of Ti6Al4V Alloy by Pack Siliconizing Method, (2018) 1024–1027.

[12] A.E. Kochmańska, A. Jarlaczyńska, J. Baranowska, Formation of silicide and silicide-aluminide coatings on molybdenum alloy during slurry cementation process: Influence of slurry volume, Materials (Basel). 14 (2021). https://doi.org/10.3390/ma14226940.

[13] T. Shimozaki, T. Okino, M. Yamane, Y. Wakamatsu, M. Onishi, Effect of impurities on growth of Ti silicides in bulk Ti/Si diffusion couple, Mater. Trans. JIM. 38 (1997) 865–870. https://doi.org/10.2320/matertrans1989.38.865.

[14] A. Paul, S. Divinski, Handbook of Solid State Diffusion, First edit, Elsevier Inc., 2017.

[15] B. Cockeram, G. Wang, The influence of multi-layered kinetics on the selection of the primary phase during the diffusion-controlled growth of titanium-silicide layers, 1995.

[16] C.M. Cotell, J.A. Sprague, F.A. Smidt, R. Menezes Nunes UFRGS, R.K. Asher, D.W. Benjamin AlliedSignal Aerospace, L. Keith Bennett Alon Processing Inc, A. Blair, R.R. Brookshire Brushtronics Engineering, M.E. Browning, R.C. Buckley, J.R. Davis Davis, C.A. Deckert Shipley Company, J.S. Feeley, H.D. Ferrier, J. Quaker, Volume Chairpersons The Volume Chairpersons were Authors and Contributors, n.d.

[17] D. Vojtěch, P. Novák, P. Macháč, M. Morťaniková, K. Jurek, Surface protection of titanium by Ti5Si3 silicide layer prepared by combination of vapour phase siliconizing and heat treatment, J. Alloys Compd. 464 (2008) 179–184. https://doi.org/10.1016/j.jallcom.2007.10.020.

[18] C. Nobili, F. Nava, G. Ottaviani, M. Costato, G. DE Santi, G. Queirolo, TITANIUM SILICIDE FORMATION IN PRESENCE OF OXYGEN, 1992.

Review Paper
Journal of Smart Systems Research (JOINSSR) 3(1), 22-29, 2022
Recieved: 28-May-2022 Accepted: 24-June-2022

SAKARYA UNIVERSITY
OF APPLIED SCIENCES

Piezoelectric Fans: A Narrative Review

Hamid ASADI DERESHGI[1*], Huseyin DAL[2], Rabia Güzide AL[1]

[1]Department of Biomedical Engineering, Istanbul Arel University, 34537 Istanbul, Turkey
[2]Department of Mechanical Engineering, Sakarya University, 54050 Sakarya, Turkey

ABSTRACT

Piezoelectric Zirconate Titanate (PZT) is a material that has many applications. One of its application is in piezoelectric (PE) fans. PZT material that acts as an actuator, by sticking to the surface of a beam or plate-like structural element, or by embedding in it a sandwich blade is obtained. The blade in the shape of a beam or plate is exposed to vibration by applying AC voltage to the PZT actuator. The blade that is exposed to vibration ensures the removal of hot ambient air. In recent years, PE fans have been used in technologically sensitive areas for heat transfer due to some important advantages. Therefore, literature survey shows that there are many studies about fans with PE actuators. In this review paper the historical background and the research areas of studies on PE fans are explained in detail to readers. Studies on the electro-mechanical properties and components of PE fans are described in detail. In addition, innovative analytical, numerical and experimental studies on PE fans in the open literature were investigated. Finally, the visual representations of the physical and experimental models used in the studies are summarized in a table. According to literature survey, it is clear that studies on PE fans have only recently begun and are gradually advancing. In particular, analytical modeling and fan blade solving methods, vibration control, blade-actuator optimization for optimum energy performance with minimum energy, experimental setups to accurately measure blade velocity and performance, the types of used PZT materials are the most popular research topics.

Keywords: Piezoelectric fans, vibrating cantilevers, heat transfer enhancement

1 Introduction

The piezoelectric effect is a linear-electromechanical reaction between electrical and mechanical conditions in insulating materials and crystals that do not have a central symmetry [1-2]. Piezoelectricity is the conversion of mechanical energy into electrical energy or electrical energy into mechanical energy [3]. In recent years, the reverse piezoelectric effect has attracted the attention of researchers with the development of microelectromechanical systems [4]. One of the important elements based on piezoelectric crystal is fans [5]. PE fans were preferred as a low-consumption tool in various industries to increase convective heat transfer [6]. PE fan with ease of operation, compact size, low noise emission, and low energy consumption, has recently become one of the preferred methods to increase heat transfer performance [7]. Fans based on PZT material are supported by various flexible blades. Applying an electric field to PZT crystal surfaces causes deformation and irregularity on its surface [8]. The piezoelectric actuator is placed on the blade with its sides clamped. Thus, horizontal expansion is converted to vertical displacement by clamping the sides of the piezoelectric actuator [9]. An alternative input signal in the piezoelectric element causes vibrations along the beam and can be used to induce

* Corresponding Author's email: hamidasadi@arel.edu.tr

fluid flow around this element and improve heat transfer. It is worth mentioning that the vibration performances of piezoelectric actuators are directly correlated with the applied amplitude and frequency. In addition, the miniaturization of PE fans has attracted the attention of researchers in recent years [10]. In this study, innovative studies on PE fans were presented. The purpose of this study was to enable researchers interested in PE fans to investigate this issue transparently. The paper is organized as follows. The factors affecting the working principles of PE fans and the innovations presented in the open literature are provided in Sections 2 and 3. Finally, the concluding remarks are reviewed in Section 4.

2 PE Fan Parameters and Characteristics

This section has been prepared to better understand the work done so far and to follow the PE fan development processes more easily. Therefore, the components and characteristic parameters of the PE fan are fully described in this section. In addition, different methods used in fan design and their advantages and disadvantages were explained based on the information available in the open literature.

2.1 The Effects of Mechanical Factors on The PE Fans Performance

In this section, the mechanical factors examined in the open literature are discussed. Thus, innovative studies in the open literature were covered in detail (see Figure 1) and the interactions of each component in the performance of PE fans are examined. For example, Liu et al. (2009) investigated parameters such as the distance of the PE fan to the heat source and the vertical or horizontal fan arrangement. It has been determined that the heat transfer performance in the horizontal fan arrangement is not less than the vertical arrangement [11]. Abdullah et al. (2009) investigated the effect of PE fan position on the heat transfer coefficient. This study was investigated by analytical and experimental methods. Consequently, it was observed that the height of the PE fan can reduce the surface temperature of the heat source to 68.9 °C [12]. Abdullah et al. (2012) investigated the effects of gap type and PE fan vibration amplitude on heat transfer. In this study, the effect of the piezoelectric actuator on the temperature distribution in two- and four-blade heatsink configurations was investigated. Finally, it has been presented that the four-bladed piezoelectric based cooler exhibits high performance [13]. Lin (2012) studied the fluid behaviour in the PE fan using analytical and experimental methods. Moreover, heat transfer was investigated in horizontal and vertical coordinates. It was concluded that the heat transfer coefficient improves 1.6-3.4 times when the heat source is in the vertical position and 1.8-3.6 times when it is in the horizontal position [14]. Huang et al. (2012) developed a three-dimensional computational model to increase the performance of PE fans. Thus, Levenberg–Marquardt Method (LMM) and CFD-ACE+ codes were used to calculate the minimum level of temperature. In addition, displacement was measured experimentally with an infrared thermal scanner. Consequently, it was noted that the optimal position of the proposed PE fan occurs at a position approximately 3.5 mm below the centre point of the fin plate [15]. Ma et al. (2013) developed a multi-fan cooling system working with PZT and magnetic forces. In addition, the distance between the fans and the heatsink and the effects of power consumption were investigated. Consequently, the temperature was reduced to 17 °C at 0.03 W power consumption under desired conditions [16]. Shyu and Syu (2014) designed a four-bladed PE fan and studied heat transfer by experimental and analytical methods. As a result, during the heat transfer enhancement between the two blade arrays of the aluminium based fan, the fans drove the airflow with a moderate Reynolds number [17]. Lin et al. (2016) proposed a five-blade PE fan based on PVC or PET. As a result, it was found that a wider blade had a greater velocity, so a narrowed blade was better for heat sources than a different rectangular shape [18]. Hales and Jiang (2018) designed a piezoelectric based multiple fan array for alternative thermal management systems. In this study, the effects of electrical factors on the performance of the PE fan were investigated. Eventually, it has been obtained that there is a linear correlation between frequency, amplitude and air flow rate [19].

Huang et al. (2021) investigated the heat transfer rate numerically and experimentally with the synthetic jet impingement method on a single fin configuration. Consequently, a linear correlation between fin array and cooling performance was obtained. Finally, horizontal fan arrangement has been found to provide better cooling [20].

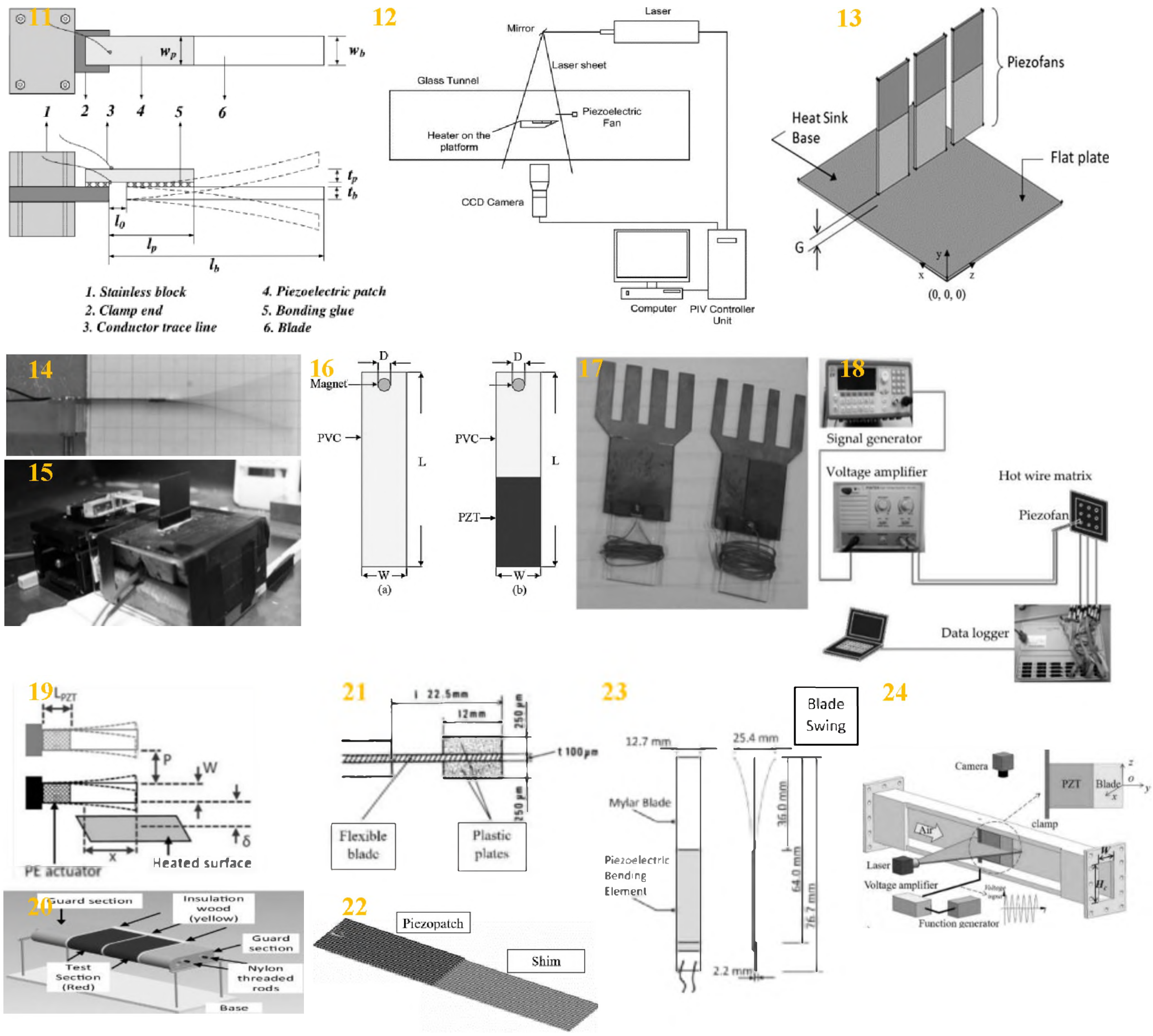


Figure 1: Structure configuration examples of PE fans

2.2 The Effects of Electrical Factors on The PE Fans Performance

In this section, the effects of electrical parameters on the performance of PE fans were investigated. There are many studies examining electrical parameters in the open literature (see Figure 1). For example, Yorinaga et al. (1985) studied the performance of the PE fan at different amplitudes. In this study, the air movement around the blade profile was investigated by the Schlieren method. The sound level of the PE fan was compared with that of the motor fan, which had the same airflow performance, Thus, it was concluded that the PE fan operates 3 dB (A) quieter than the conventional motor fan [21]. Wait et al. (2007) analysed the performance of PE fans operating in high resonance modes analytically and experimentally. An impedance analyser was used in the experimental measurements to determine the resonant frequencies. The effect of the resonance mode on the flow profile was presented with the visualization technique. Consequently, it is stated that the number of modes has linear and non-linear correlations with power consumption and flow rate, respectively [22]. Ma et al. (2015) preferred a system with two PE fans to make the heat transfer process expeditious. Thus, continuous and high heat flux at lower amplitudes was obtained [23]. Chen et al. (2020) analysed the heat transfer performance of the proposed PE fan analytically. In this study, the working principle and performance of PE fan with Structure Boundary Detection Algorithm and Fast Fourier Transform Algorithm were investigated. In addition, the heat transfer performance of the PE fan with temperature-sensitive paint was experimentally measured. Consequently, there was a 46% improvement in the performance of the proposed novel PE fan at 43 Hz [24].

3 Taxonomy of Previous Studies

There are many studies on this subject in the literature. In this section, the working principles and investigation methods of PE fans are examined in detail.

3.1 Analytical Modelling of PE Fans

This section contains innovative studies that analytically analyse the performance of PE fans. The purpose of this section is to examine the mathematical expressions used in analytical studies. There are many studies available in the open literature (see Figure 2). For example, Yao and Uchino (2001) studied the damping effect on mechanical wobbling. In addition, the effects on vibration were investigated by adding mass to the end of the plate. Consequently, magnitude deflections were obtained at low frequencies [25]. Lin (2013) used the visualization technique to study the behaviour of the fluid flow around the fan tip and cylindrical surface. In addition, three-dimensional simulations are carried out to investigate the detailed properties of the heat and fluid flow fields produced by the PE fan. Finally, the experimental results confirm the results obtained by the numerical method [26]. Li et al. (2018) proposed a dual PE fan to increase convective heat transfer performance. In addition, the effects of electrical factors on heat transfer were covered. It was observed that single and dual fans produce very close heat transfer coefficients [27]. Hu et al. (2020) analytically analysed the effects of a PE fan array in a solar air heater. Two different downstream configurations were tested, including counter flow and downstream. The results showed that the PE fan as a vortex generator can effectively increase the local and average Nusselt number [28]. Qing et al. (2020) designed a new air cooling system for a control box. The Flotherm special thermal modelling method was used for the simulation of this system [29]. Ding et al. (2020) analysed the horizontal cooling performance of a heated wall from PE fans. In this study, dynamic mesh technology is used to make analytical simulations of the air flow and heat transfer properties of the PE fan [30].

3.2 Numerical Modelling of PE Fans

Numerical analysis deals with the formulation, study and application of approximate computational methods to solve these problems of continuous mathematics (as opposed to discrete mathematics) which cannot be solved by analytical and precise methods. Innovative numerical studies on PE fans are covered in this section to examine in more detail (see Figure 2). For example, Lin (2013) simulated the heat and flow behavior around a cylindrical structure in FLUENT 3D. In conclusion, this study examined the effects of the separation distance between the fan tip and the heated surface and the amplitude of the fan tip for the cylindrical heated surface [31]. Jiahong et al. (2021) investigated the eddy change and heat transfer of the PE vibrating cantilever in liquid-cooled channels. Consequently, it was obtained that the liquid density was inversely correlated with the vortex shedding strengt and the radius of the core [32].

3.3 Experimental Analysis of PE Fans

In the open literature, there are many studies that experimentally examine the working principles and performances of PE fans (see Figure 2). In this section, studies with striking innovations are included. For example, Schmidt (1994) experimentally investigated the performance of the proposed novel PE fan. experiments were carried out using naphthalene sublimation technique with certain boundary conditions. Finally, an equivalent jet Reynolds number is presented, which will provide the same surface-averaged Sherwood number as that obtained with the PE fan, in comparison of the present experimental results with the jet impingement flow [33]. Acikalin et al. (2004) proposed a PE fan for the cooling of portable electronic devices [34].

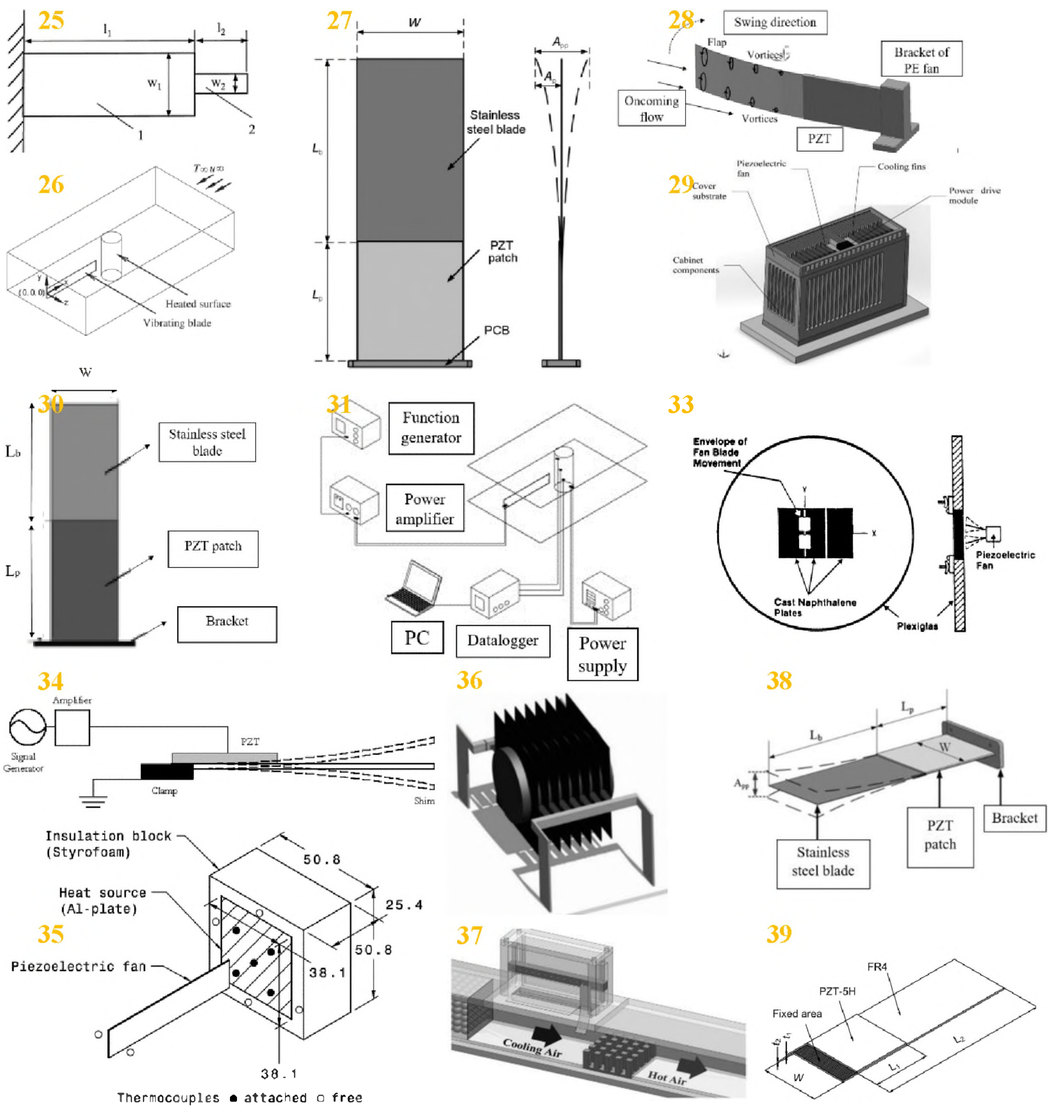


Figure 2: Studies on PE fan technology

Açıkalın et al. (2007) analysed the potential of using PE fans in the thermal management of electronic components analytically and experimentally. The Design of Experiments (DOE) approach was used for experimental design. As a result, a 375% increase in the convective heat transfer coefficient was achieved, resulting in a temperature drop of more than 36.4% at the heat source [35]. Gilson et al. (2012) prepared two different experimental setups for fluid flow characterization and the thermal enhancement capabilities. Consequently, it has been obtained that the Fin Side Walls (FSW) fan is not as efficient as the Fin Base (FB) in cooling [36]. Jeng and Liu (2015) experimentally investigated the effect of the air flow in the blade and the heat-collecting receiver on the heat transfer [37]. Li et al. (2017) studied the convective heat transfer output of cross-flow around the vibration envelope of a PE fan. As a result, it was observed that the combined performance of fan-induced heat transfers and fan vibration envelope improves the convective heat transfer that occurs near the fan vibration envelope [38]. Qiu et al. (2020) investigated the local heat transfer enhancement caused by a PE fan interacting with axial flow in the heated channel. The experimental result showed that the heat transfer performance of the heated surfaces is greatly enhanced by a vibrating PE fan. In the simulations, the spring-based smoothing method and the local remeshing technique were used to solve the moving boundary problems. Finally, the numerical result shows that the increase in heat transfer is obtained from the vortex pairs generated by the PE fan, which significantly enhances the heat exchange between the main flow and the near-wall flow [39].

4 Conclusions

In this study, researches on PE fans in the open literature were investigated in detail. Analytical, numerical, and experimental methods were used in the studies. Three-dimensional computational models have been developed. Almost all studies have shown that PE fans have high performance in the field of heat transfer. Low energy consumption, controllability, design and fabrication facility, compact and small size, safe and long life can be considered as the most important advantages of PE fans. Ultrasonic high-frequency noise is identified as its most important disadvantage. There is a wide selection of materials for PE fans and actuator blades. The width of the blade and PE actuator increases performance. In addition, increased blade stiffness reduces fan performance. In multi-blade PE fans, the number of blades has a significant effect on the Nusselt number. It has been determined that the Schlieren type PE fan operates 3 dB quieter than the conventional motor fan. It has been stated that the number of PE patches used in the fan blade reduces the power. It is found that the vibration mode with the best performance is the first vibration mode. Higher modes reduce performance and energy consumption.

5 Declarations

5.1 Study Limitations

None.

5.2 Acknowledgements

Special thanks to the ArelMED-I members for their motivations, recommendations and feedback.

5.3 Funding Source

None.

5.4 Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

5.5 Authors' Contributions

Hamid ASADI DERESHGI contributed with the paper writing and revisions.

Huseyin DAL contributed with the paper writing and revisions.

Rabia Güzide AL contributed with the paper writing and revisions.

References

[1] Asadi Dereshgi, H., Dal, H., & Sayan, M. E. (2020). Analytical analysis of a circular unimorph piezoelectric actuator in the range of low voltages and pressures. Microsystem Technologies, 26(8), 2453-2464.

[2] Anton, S. R., & Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003–2006). Smart materials and Structures, 16(3), R1.

[3] Sodano, H. A., Inman, D. J., & Park, G. (2004). A review of power harvesting from vibration using piezoelectric materials. Shock and Vibration Digest, 36(3), 197-206.

[4] Maaspuro, M. (2016). Piezoelectric oscillating cantilever fan for thermal management of electronics and LEDs—A review. Microelectronics Reliability, 63, 342-353.

[5] Hales, A., & Jiang, X. (2018). A review of piezoelectric fans for low energy cooling of power electronics. Applied Energy, 215, 321-337.

[6] Park, S. H., Park, G. J., & Choi, S. D. (2004). Heat Transfer Characteristics Around a Surface-Mounted Module Cooled by Piezoelectric Fan. Transactions of the Korean Society of Mechanical Engineers B, 28(7), 780-788.

[7] Açıkalın, T., Raman, A., & Garimella, S. V. (2003). Two-dimensional streaming flows induced by resonating, thin beams. The Journal of the Acoustical Society of America, 114(4), 1785-1795.

[8] Park, S. H., Oh, M. H., Kim, Y. H., & Choi, M. (2019). Effects of freestream on piezoelectric fan performance. Journal of Fluids and Structures, 87, 302-318.

[9] Kimber, M., Suzuki, K., Kitsunai, N., Seki, K., & Garimella, S. V. (2008, May). Quantification of piezoelectric fan flow rate performance and experimental identification of installation effects. In 2008 11th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (pp. 471-479). IEEE.

[10] Chen, Y., Li, J., Wang, Z., Yan, Y., & Cui, J. (2021). Unsteady Flow Characteristics of an Oscillating Piezoelectric Fan Blade at High Reynolds Numbers. Applied Sciences, 11(20), 9510.

[11] Liu, S. F., Huang, R. T., Sheu, W. J., & Wang, C. C. (2009). Heat transfer by a piezoelectric fan on a flat surface subject to the influence of horizontal/vertical arrangement. International Journal of Heat and Mass Transfer, 52(11-12), 2565-2570.

[12] Abdullah, M. K., Abdullah, M. Z., Ramana, M. V., Khor, C. Y., Ahmad, K. A., Mujeebu, M. A., ... & Ripin, Z. M. (2009). Numerical and experimental investigations on effect of fan height on the performance of piezoelectric fan in microelectronic cooling. International Communications in Heat and Mass Transfer, 36(1), 51-58.

[13] Abdullah, M. K., Ismail, N. C., Abdullah, M. Z., Mujeebu, M. A., Ahmad, K. A., & Ripin, Z. M. (2012). Effects of tip gap and amplitude of piezoelectric fans on the performance of heat sinks in microelectronic cooling. Heat and Mass Transfer, 48(6), 893-901.

[14] Lin, C. N. (2012). Analysis of three-dimensional heat and fluid flow induced by piezoelectric fan. International Journal of Heat and Mass Transfer, 55(11-12), 3043-3053.

[15] Huang, C. H., Chen, Y. F., & Ay, H. (2012). An inverse problem in determining the optimal position for piezoelectric fan with experimental verification. International Journal of Heat and Mass Transfer, 55(19-20), 5289-5301.

[16] Ma, H. K., Su, H. C., & Luo, W. F. (2013). Investigation of a piezoelectric fan cooling system with multiple magnetic fans. Sensors and Actuators A: Physical, 189, 356-363.

[17] Shyu, J. C., & Syu, J. Z. (2014). Plate-fin array cooling using a finger-like piezoelectric fan. Applied Thermal Engineering, 62(2), 573-580.

[18] Lin, C. N., Jang, J. Y., & Leu, J. S. (2016). A study of an effective heat-dissipating piezoelectric fan for high heat density devices. Energies, 9(8), 610.

[19] Hales, A., & Jiang, X. (2018). A review of piezoelectric fans for low energy cooling of power electronics. Applied Energy, 215, 321-337.

[20] Huang, L., Yeom, T., Simon, T., & Cui, T. (2021). An experimental and numerical study on heat transfer enhancement of a heat sink fin by synthetic jet impingement. Heat and Mass Transfer, 57(4), 583-593.

[21] Yorinaga, M., Makino, D., Kawaguchi, K., & Naito, M. (1985). A piezoelectric fan using PZT ceramics. Japanese Journal of Applied Physics, 24(S3), 203.

[22] Wait, S. M., Basak, S., Garimella, S. V., & Raman, A. (2007). Piezoelectric fans using higher flexural modes for electronics cooling applications. IEEE transactions on components and packaging technologies, 30(1), 119-128.

[23] Ma, S. L., Chen, J. W., Li, H. Y., & Yang, J. T. (2015). Mechanism of enhancement of heat transfer for plate-fin heat sinks with dual piezoelectric fans. International Journal of Heat and Mass Transfer, 90, 454-465.

[24] Chen, Y., Peng, D., & Liu, Y. (2020). Heat transfer enhancement of turbulent channel flow using a piezoelectric fan. International Journal of Heat and Mass Transfer, 147, 118964.

[25] Yao, K., & Uchino, K. (2001). Analysis on a composite cantilever beam coupling a piezoelectric bimorph to an elastic blade. Sensors and Actuators A: Physical, 89(3), 215-221.

[26] Lin, C. N. (2013). Enhanced heat transfer performance of cylindrical surface by piezoelectric fan under forced convection conditions. International Journal of Heat and Mass Transfer, 60, 296-308.

[27] Li, X., Zhang, J., & Tan, X. (2018). Experimental and numerical investigations on convective heat transfer of dual piezoelectric fans. Science China Technological Sciences, 61(2), 232-241.

[28] Hu, J., Jing, C., & Zhao, Y. (2020). Heat transfer enhancement research of dynamical vortex generator in a solar air heater by using the piezoelectric fan array. Heat and Mass Transfer, 56(3), 825-847.

[29] Qing, L., Kun, W. A. N. G., Can, L., & Min, W. (2020, August). A New cooling system based on Piezoelectric fan. In Journal of Physics: Conference Series (Vol. 1605, No. 1, p. 012056). IOP Publishing.

[30] Ding, P., & Liu, Z. (2020, November). Study on the Convective Heat Transfer Characteristic of a Horizontal Piezoelectric Fan. In Journal of Physics: Conference Series (Vol. 1670, No. 1, p. 012013). IOP Publishing.

[31] Lin, C. N. (2013). Heat transfer enhancement analysis of a cylindrical surface by a piezoelectric fan. Applied Thermal Engineering, 50(1), 693-703.

[32] Fu, J., Chen, Y., Yu, Z., & Zhang, X. (2021). Enhanced heat transfer research in liquid-cooled channel based on piezoelectric vibrating cantilever. Thermal Science, 25(2 Part A), 823-832.

[33] Schmidt, R. R. (1994, May). Local and average transfer coefficients on a vertical surface due to convection from a piezoelectric fan. In Proceedings of 1994 4th Intersociety Conference on Thermal Phenomena in Electronic Systems (I-THERM) (pp. 41-49). IEEE.

[34] Acikalin, T., Wait, S. M., Garimella, S. V., & Raman, A. (2004). Experimental investigation of the thermal performance of piezoelectric fans. Heat Transfer Engineering, 25(1), 4-14.

[35] Açıkalın, T., Garimella, S. V., Raman, A., & Petroski, J. (2007). Characterization and optimization of the thermal performance of miniature piezoelectric fans. International Journal of Heat and Fluid Flow, 28(4), 806-820.

[36] Gilson, G. M., Pickering, S. J., Hann, D. B., & Gerada, C. (2012). Piezoelectric fan cooling: A novel high reliability electric machine thermal management solution. IEEE Transactions on Industrial Electronics, 60(11), 4841-4851.

[37] Jeng, T. M., & Liu, C. H. (2015). Moving-orientation and position effects of the piezoelectric fan on thermal characteristics of the heat sink partially filled in a channel with axial flow. International Journal of Heat and Mass Transfer, 85, 950-964.

[38] Li, X. J., Zhang, J. Z., & Tan, X. M. (2017). Convective heat transfer on a flat surface induced by a vertically-oriented piezoelectric fan in the presence of cross flow. Heat and Mass Transfer, 53(9), 2745-2768.

[39] Qiu, Y. L., Wu, C. J., & Chen, W. F. (2020). Local heat transfer enhancement induced by a piezoelectric fan in a channel with axial flow. Journal of Zhejiang University-SCIENCE A, 21(12), 1008-1022.

Research Paper
Journal of Smart Systems Research (JOINSSR) 3(1), 30-48, 2022
Recieved: 03-June-2022 Accepted: 28-June-2022

SAKARYA UNIVERSITY
OF APPLIED SCIENCES

Design of A 3-DOF Thrust Control System for Rocket Engines

Haktan YAĞMUR[1*], Can BAYAR[1], Sinan ŞEN[1], Kasım SERBEST[1]

[1] Department of Mechatronics Engineering, Faculty of Technology, Sakarya University of Applied Sciences

ABSTRACT

Within the scope of this paper, a system that can direct the thrust of solid propellant rocket engines will be built. This method will provide high mobility for hybrid and liquid propellant rocket engines. The rocket will react to external effects (wind, etc.) that may occur while cruising. Sensors such as GYRO and IMU on the system are called TVC (Propulsion Vector Control), which provides the balance of the rocket by directing the thrust in the opposite direction of the rocket's trajectory. It also meets the requirements for angular speed control, route linearity and immediate response to emergencies. The design of the system has been created according to geometric properties, kinematics and forces, energy requirements, safety, cost, control methods requirements. Regarding the management of TVC, a literature review on TVC system design has been made first. Analyzes will be made taking into account the thrust and combustion time of the engine used. The system will be designed according to mechanical and avionic design principles. All of this is filtered out by focusing on the relevance, adaptability, economy and consistency of production. It is aimed to solve and support the software and algorithms to be created (differentiated design), thrust vector angular position and other motion problems through flow charts. With the possible design we mentioned in the report, we aim to solve similar examples of our project and to eliminate the question mark in our minds to some extent. Our project management will be carried out in accordance with work schedules, risk management and research facilities. We aim to work on projects such as literature research, system conceptual design, system visual design, preparation of the final design and the final report of the system.

Keywords: Thrust vector control, conceptual design, engineering design, product developming

1 Introduction

Propulsion Orientation consists of the modulation of the thrust vector in a variable direction other than the axial direction. The practical application of the thrust vector is achieved by mechanically turning the nozzle in different directions. By forcing and manipulating the flow in a nozzle with fixed geometry, the same effect can be achieved without operating mechanical equipment [1]. The second method, Fluid Drive Direction (FTV), uses auxiliary vents to actively manipulate and control the primary airflow to the breast. The injected fluid forms a variable "artificial" nozzle border, and the discomfort caused by secondary flow strain makes the breast wall pressure distribution asymmetrical. The resulting effect is a lateral force on the breast, which can be seen as the lateral component of the thrust vector.

In addition to providing a propellant to the rocket, it can provide moments to rotate the rocket. Therefore, it can control the attitude of the rocket and the path of flight. The direction of the propulsion

[*] Corresponding Author's email: haktanyagmur33@gmail.com

vector can be controlled by the mechanism, controlling the rolling and rolling motion of the rocket, and this control is effective only when the propulsion system is running and generating exhaust jets. During the flight, when the rocket propulsion system is not fired, and therefore the propulsion vector control does not work, the rocket must be provided with a separate mechanism to maintain control of its own state or flight path. In this context, the guidance of the system operating with the help of servo motors is determined as the main purpose of this article [2].

Within the scope of this article, a system capable of directing the thrust from solid-fuel rocket engines will be made. This approach will provide high maneuverability for hybrid and liquid-fueled rocket engines. The rocket will react to external influences (wind, etc.) that may occur while traveling. Sensors such as gyroscope and pressure on this system, called TVC (Thrust Vector Control), ensure to keep the rocket in balance by directing the thrust in the opposite direction of the rocket trend. It also meets requirements such as angular speed control, route linearity, and instant reaction to unexpected situations. There will be 2 servo motors on the thrust steering system. The servo motors are positioned to move on the X-axis and the Y-axis, and thanks to the gyroscope sensor on the system, the motors angle in the opposite direction of the rocket trend and the nozzle is moved by the shafts connected to the motor [3].

The design of the system is formed in accordance with the requirements of geometric properties, kinematics and force, energy requirements, safety, cost, control and operating methods. In order to manage TVC, a mixed mathematical model was first put forward by conducting a literature search for TVC system design. Analyses will be carried out by considering parameters such as the thrust force of the engine used, the burning time. The system will be designed based on avionics and mechanical design principles specific to aerospace disciplines. All these are filtered with care for suitability for production, easy integration, economy and consistency. With the software and algorithms to be created, the problems were intended to solve movements such as the angular position of the thrust vector and were supported by flow diagrams [4].

The mechanism made in this study works more effectively than systems such as Vacuum-Compatible 6-Axis Hexapod. It also includes the same avionics and software components as other Thrust Vector Systems. In this way, a design that can be integrated into all low altitude rockets has been revealed. The accuracy of all calculations and cost analyzes used in the production of the system has been examined. The design and software have been optimized for the stable operation of the system.

1.1 Movement of Rockets

Rockets are mainly aimed at getting out of the influence of the force of gravity. For this reason, a rocket must get rid of gravity in order to take off. If a force does not act on the rocket, the rocket naturally retains its status due to the law of immobility. In this part, the rocket engine comes into play. The task of the engine is to create the power to the rocket to move itself.

The rocket engine is powered by gases. For this, the gases suitable for rocket construction are heated with very high temperature. With this heat, the gas molecules begin to move rapidly, and the spraying effect caused by the movement of the gas exerts a force, which in turn moves the rocket.

It is not easy for the rocket to move from a state of immobility to a moving state. For example, your car moves comfortably on the highway thanks to its rotating wheels, or a train pushes the tracks backwards and moves forward. But there is no ground on which the rocket will receive power in this way. Rockets, therefore, ensure their movement in space with Newton's law of motion, known by Newton's statement that "there is a reaction to every effect" [5].

1.2 Rocket Fuel Preferences

There are two characteristics that are important in the selection of fuels used in spacecraft; The first is the change caused by a certain amount of fuel in the momentum of the spacecraft. The second is the magnitude of the thrust force generated by the fuel. The magnitude of the thrust is of great importance. A rocket needs to reach a speed of 28,000 km to orbit a satellite, and 40,000 km to escape the gravitational pull of the same rocket. At the same time in the selection of fuel; the stability of the fuel, its easy and safe storage and its cost are also considered. Rocket fuels are generally divided into two, liquid rocket fuels and solid rocket fuels. In rockets where liquid fuels are used, fuel and liquid oxygen are sent to the reservoir where combustion will take place. The thrust caused by the gas generated by the combustion as it exits the rocket accelerates the rocket [6].

The history of solid fuels goes back to earlier than liquid fuels. But they are not very preferable. This is because the speed of the rocket cannot be controlled as desired when they are burned. At the same time, it is not possible to stop solid fuels after reacting. For this reason, solid fuels are mostly used in support rockets that are separated from the original rocket after providing the initial speed that the rocket needs.

1.3 Solid Fuel Rocket Engines

The best part of solid-fuel rockets is that they are simple. The rocket simply consists of three parts. The first part is the load (satellite or explosive), the second part is a single fuel tank with a combination of flammable and caustic material, and the third part is exhaust. They are usually used to carry loads in or to the upper parts of the atmosphere. There is no engine assembly that allows and controls the combustion of fuel. They are the most widely used types of rockets in the military field. They can be very small in volume and size compared to liquid-fueled rockets. In the military, rockets used against tanks and planes over the shoulder use this type of fuel. They have larger wings so that they do not deviate from their course due to the resistance of air in the atmosphere [7].

In solid-propellant rockets, flammable and caustic substances are mixed homogeneously as much as possible. Therefore, if the mixture is not homogeneous, it causes regional explosions in the rocket's combustion chamber and exhaust output, so the rocket's speed is not regular. Their biggest advantage is the high thrust power. They provide thrust twice as great as liquid-fueled ones. Since the exhaust temperatures are very high, the fuel tank and the exhaust must be very robust. Some rockets have some additional devices that cool the exhaust. There is no mechanism that controls the speed and burning rate of the rocket. The absence of additional devices can be considered an advantage in one place, as it reduces the load of the rocket.

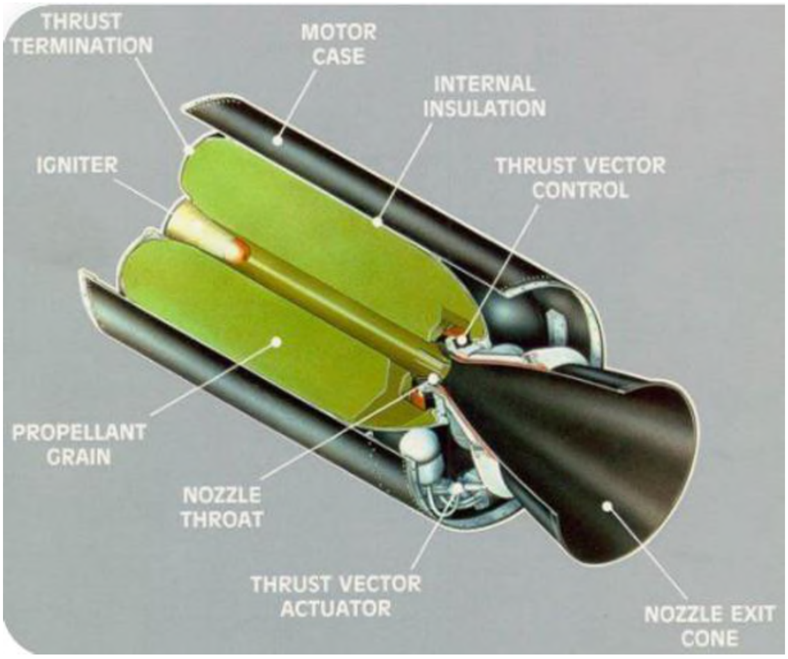


Figure 1: Cut image of solid fuel rocket engine [7]

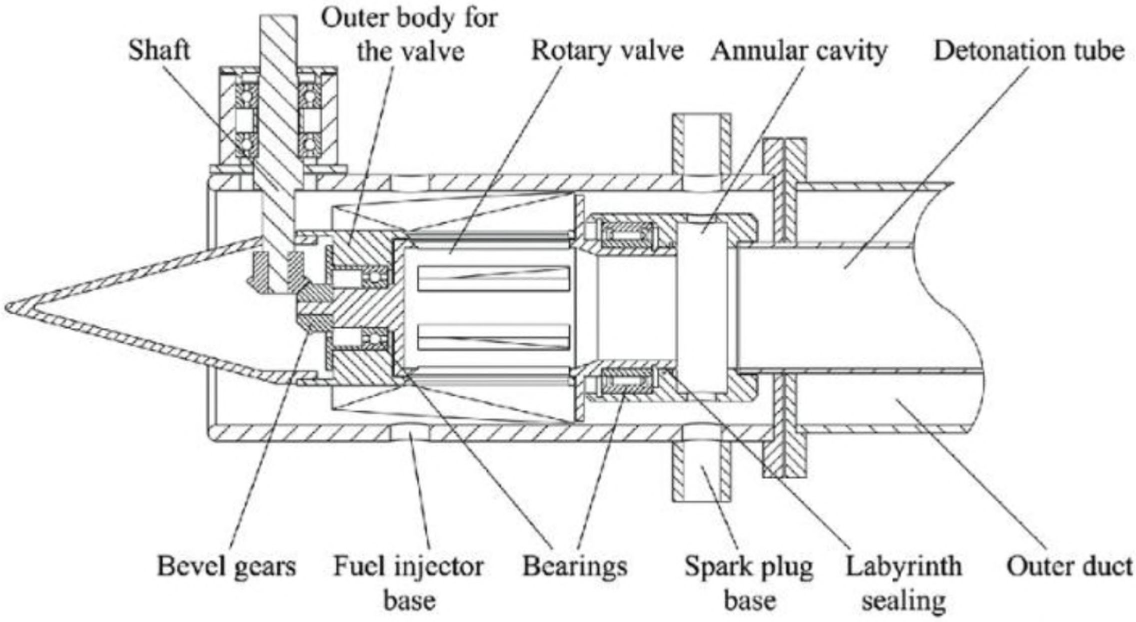


Figure 2: Detonated views of the solid-fuel rocket engine [7]

1.4 Flexible Nozzle Joint

Flexible articulated TVC systems are used today in large strategic and satellite launch systems, as well as tactical systems that require a vector angle of 5°−15°. Flexible nozzle joints have a layered structure, which is formed by gluing and reinforcing the elastomer. Its layers are connected to each other together with the front and back rings. Orientation is achieved through shear deformation of elastomeric layers. Reinforcing layers are made of metal (steel) or composites. Elastomers used so far, silicone, natural rubber and synthetic polyisoprenes. These elastomers are used at a wide range of temperatures, making them suitable for submerged nozzles. With increasing vector angle, pressure, flexible joint torque values increase and create deformation in a shorter time. The general application in this type of nozzle joints is spherical, but there are applications of tapered design. When deflected at an angle in any direction, the layers of elastomer are subjected to cutting. The deformation and hardness of the rotated layers with a certain ratio of the total vector may vary depending on the angle. Flexible nozzle connection design involves the choice of connection configuration, the number of reinforcing elements and the choice of material can vary according to multiple factors such as elastomers [8].

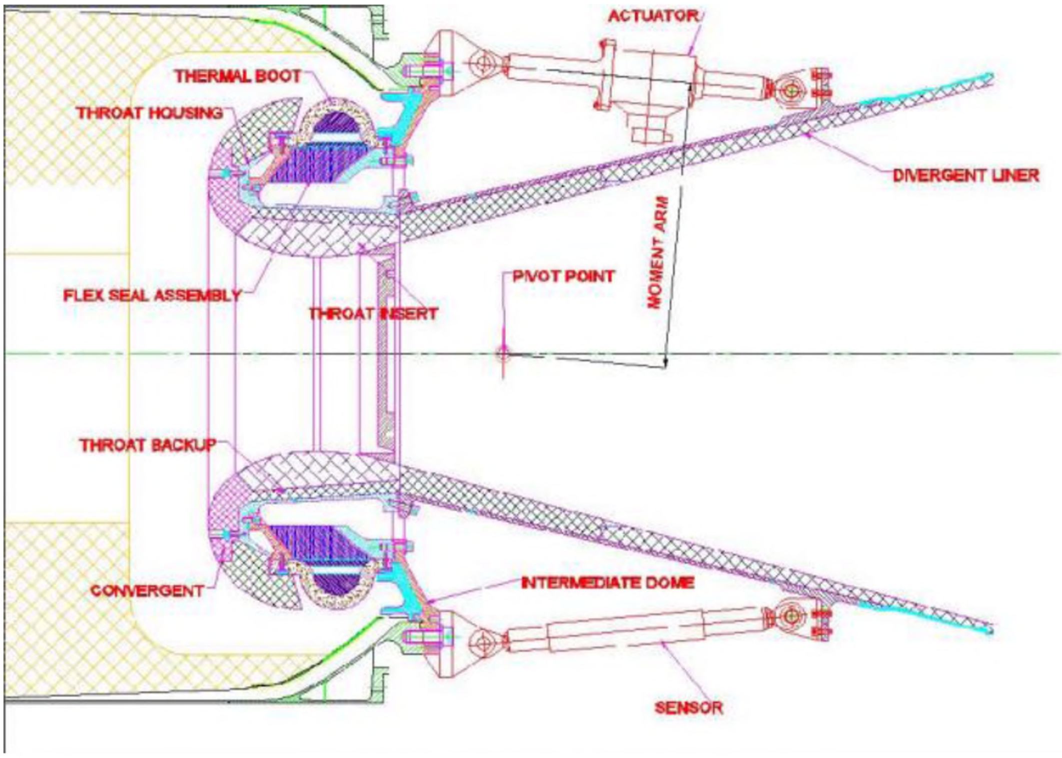


Figure 3: Flexible nozzle joint design [8]

1.5 Jet Deflector / Jet Tab / Jetavator TVC Systems

In these systems, mechanical deflectors are placed around the exit zone of the nozzle and the propulsion vector control is provided by this deflector located at the outlet. They do not create a rolling moment on these systems. Jet deflectors and jet tabs have blunt structures created to prevent flow at the nozzle outlet. Therefore, the use of jet deflectors and jet blades causes excessive loss of power. The JD at the end of the insertion nozzle causes the shock wave to occur before the deflector, and the pressure on the deflector increases. The resulting pressure increase also creates a side force.

This side force is directly proportional to the values of the JD field. The side force is adjusted by moving the JD at the nozzle output to enlarge and decrease the nozzle output area differs for side force.

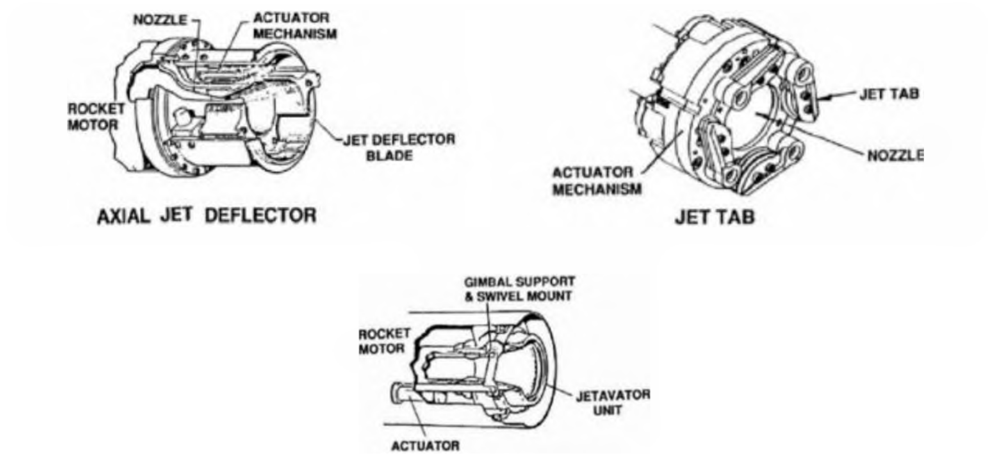


Figure 4: Jet wings and jet deflectors-tabs [8]

1.6 TVC System With Jet Valve

Jet Vane TVC systems are one of the effective TVC systems used in missiles. In TVC systems with jet wings, a blade is placed at the nozzle outlet and at the base of the blade. It follows the contour of the nozzle. In addition to the rolling moment relative to the center line, the jet creates moments of wobble and wobble. Jet wing control work was first used on the German V-2 missile. The sash is characterized by any small fins or plates that are located directly at the outlet. The principle of creating control forces using the flow of the nozzle, the wings, to control the thrust vector is like generating supersonic wing buoyancy. In the upward movement, the pressure difference and the lower sides of the jet wing provide a normal force to the beam of the jet. Normal force has a component in the direction of lifting, it is also called the side force. It is useful to control the force and missile with a security system. The main purpose of the design of a jet wing is to create a side wing. What is really created here is that there is no loss of force with minimal drag [9].

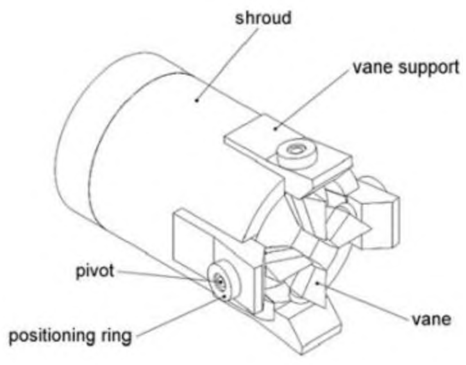


Figure 5: Jet propeller system [9]

2 Methodolgy

2.1.1 Propulsion Guidance System Design Specification

The design specification of the Propulsion Guidance System to be made here is aimed to be tabular and a more stable design is revealed.

Demands (D) are the characteristics that the nature-inspired system must meet. Wihes (W) refers to the secondary characteristics that can be found in the device.

Table 1: Design Specification

DESIGN SPECIFICATION			
	D/W		**D/W**
Geometric Features: • Parts can be produced easily. • Easy to integrate into the rocket • Designing the parts so that they are intertwined • System consistency	**D**	**Security:** • Enviromental Security • Material Safety	**D**
		Cost: • Be Comptetive	**W**
Kinematics and Force: • Have a high degree of freedom • The inertia unit provides relationships between command angles, servo motors connected to the spindle and system position • Defining an internal fixed reference	**W**	**Control And Operation** • Ease of assembly • Propulsion Vector Control • Digital control	**W** **D** **W**
Energy Requirement: • There is an energy need to drive avionics systems and servo drives along the route. • Low voltage	**D**	**Material:** • Rigidity • High temperature resistance • Durability • Lightness	**D** **W** **W** **W**

2.1.2 Overall Function

Overall function of the system; The energy input of the system is referred to as the electrical energy of the servo motors, the energy output of the system is also referred to as the mechanical energy generated. The thrust guidance system, which is designed as material input, is discussed. The material output is the delivery of the product to the customer. The signal input is the operation of the system through the control unit, the signal output is the system movement with the servo motor movement in 2 axes with the energy we provide from the battery [10].

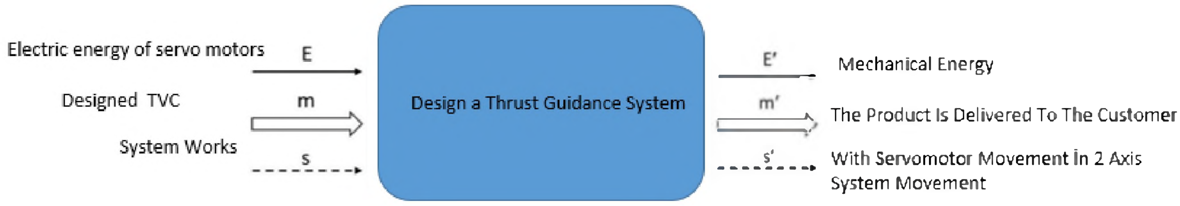


Figure 6: Overall function

2.1.3 Subfunctions

The subfunctions of the generated thrust guidance system are determined. According to the determined aerodynamic limitations, the rocket body is formed, and the product is obtained. According to the area of use, it is used in tasks such as vertical landing rocket steering, space space activities and directing warplanes.

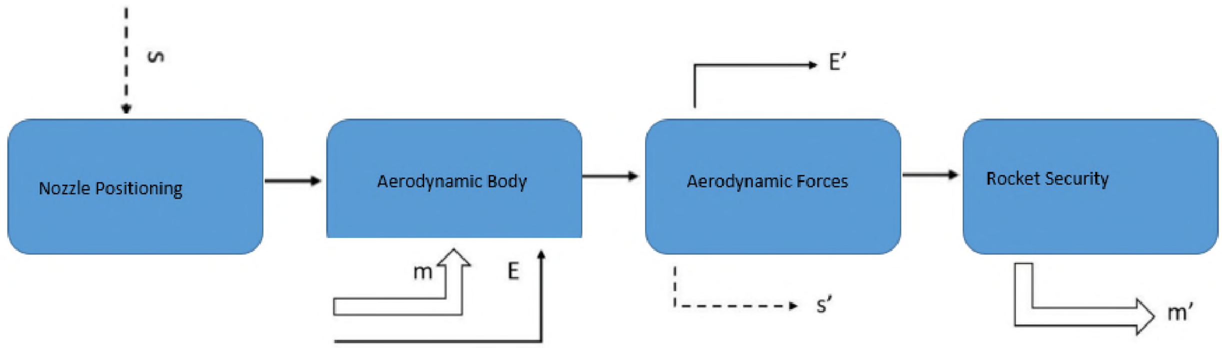


Figure 7: Subfunctions

2.1.4 Possible Designs

Movable Nozzle Thrust Vector Control Systems

The combustion gas is vectorized and moved by the deflection of the nozzle to achieve the desired thrust vector control. Moving nozzle systems are one of the most efficient. Since the system produces a thrust vector, the loss is much less than other systems.

TVC systems with moving nozzles do not have mechanical deflectors or other deflectors that can alter the nozzle angle and cause a loss of axial thrust in the flow [11].

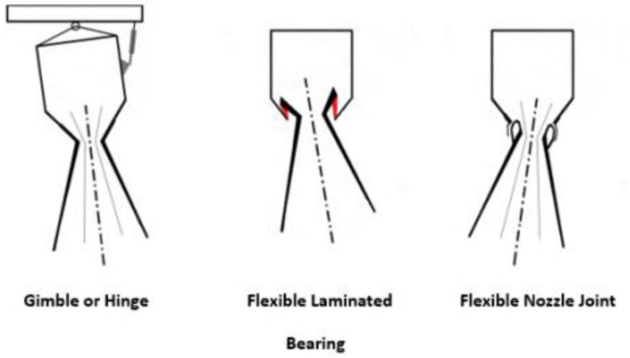


Figure 8: Movable nozzle control systems [11]

Gimbal Type Nozzle

TVC systems with movable nozzles are classified according to minor differences. In moving nozzle systems, the divergent part of the nozzle can be rotated independently. In the moving TVC system, the external geometry is divided into two parts: the throat and the fixed part. The expansion part is the moving part, and the moving part is the fixed part. The outer geometry of the most moving part is rounded and integrated like a hinge so that the fixed part can rotate around (Figure 4).

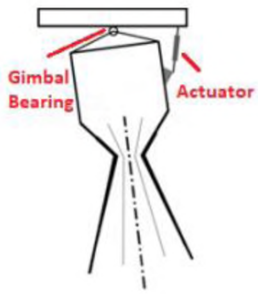


Figure 9: Gimbal type nozzle [11]

Fixed Nozzle Propulsion Vector Control Systems

In these systems, thrust vector control is provided by deflecting the exhaust gases of the rocket engine using mechanical obstacles. Such systems use a jet flap or a jet deflector. Jet wings, which mechanically change the direction of flow in the nozzle outlet area, change the direction of flow with small wings placed on the inner surface of the aircraft and provide rotational torque over jet deflector systems.

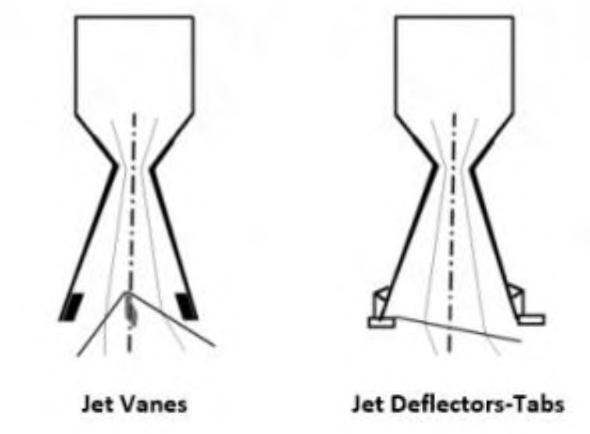


Figure 10: Fixed nozzle control system [11]

Secondary Injection Propulsion Vector Control Systems

TVC systems with secondary injection work on the principle that the flow of propellants in a fixed nozzle is driven by another secondary hot or cold gas injected (Figure 4). The secondary injection directs the flow of gas in the nozzle by disrupting the supersonic flow to create an oblique shock wave. An impulse vector is provided by the torque produced [12].

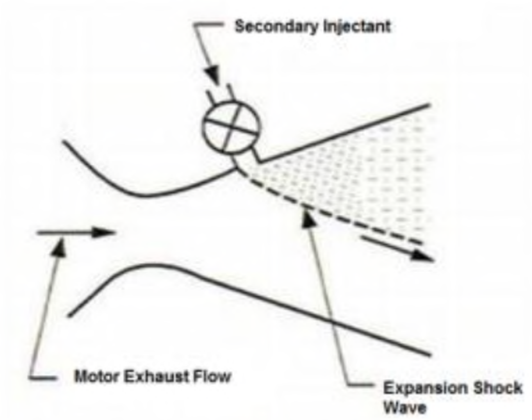


Figure 11: Secondary injection control systems [12]

Evaluation of Proposed Solutions

Determined criteria; easy maneuverability, reliability aviation compliance, aerodynamic structure, light weight are the features expected in the vehicle

• Easy maneuverability: The length, position and dimensions of the designed system should be done carefully for the system to maneuver easily in the air and to ensure smooth air climbing and advancing.

• Reliability: flight safety, electrical and systemic security of the system must be ensured.

• Aaerodynamic structure: Since the vehicle will be exposed to high altitude and aerodynamic forces in the air, the external structure must be designed appropriately according to aerodynamic forces and resistances.

• Lightness: The total rocket weight is required to be at the lightest values with payload so that the system can travel longer distances while moving through the air [13].

Objective Tree

There are 5 criteria determined in the vehicle such as easy maneuverability, reliability, aerodynamic structure suitable for public transport and individual use, lightness. It has a weighted value of 20% of all these determined criteria [14].

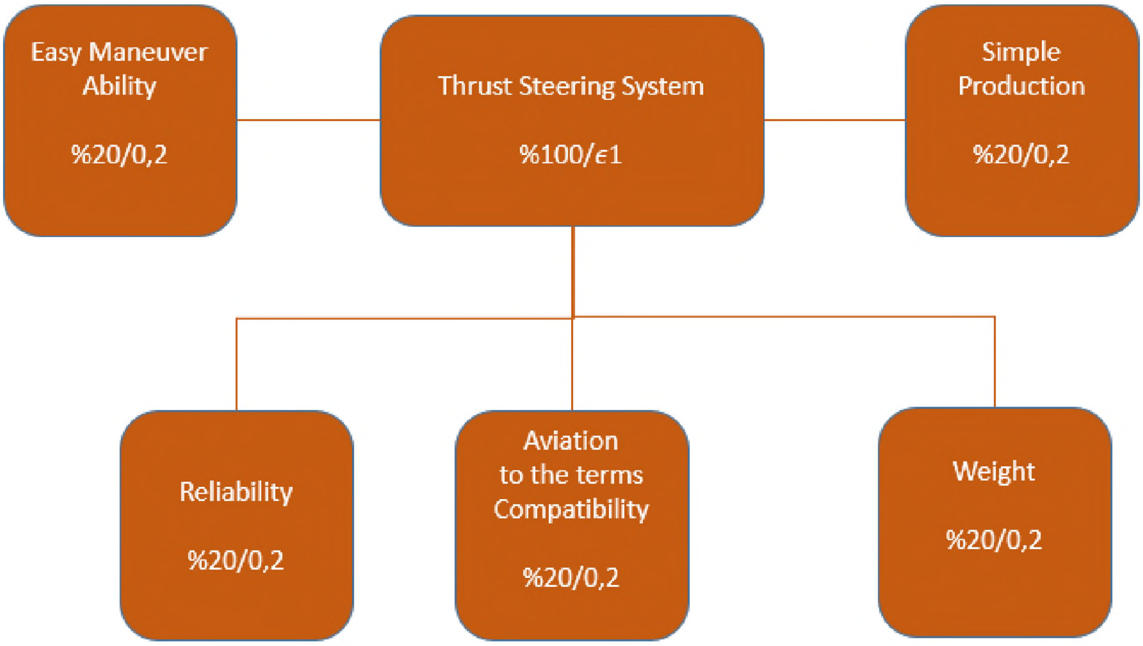


Figure 12: Objective Tree

Table 2: Evaluation of solutions

Value Analysis		**Movable Nozzle Thrust Vector Control Systems**		**Gimbal Type Nozzle**		**Fixed Nozzle Propulsion Vector Control Systems**		**Secondary Injection Propulsion Vector Control Systems**	
Criteria	Ratio	Value	w	Value	w	Value	w	Value	w
1) **Maneuverability**	0,2	1	0,2	2	0,6	3	0,5	3	0,5
2) **Cost-Effectivenes**	0,2	2	0,8	2	0,2	2	0,6	2	0,6
3) **Reliability**	0,2	3	0,5	2	0,5	2	0,8	2	0,8
4) **Aviation Compliance**	0,2	2	0,2	2	0,5	2	0,65	2	0,65
5) **Simple Production**	0,2	2	0,9	1	0,2	1	0,8	1	0,8
6) **Weight**	0,2	1	0,8	2	0,2	3	0,7	3	0,7
TotalΣ	**Σ = 1**	**Σw = 4.5**		**Σw = 3,85**		**Σw = 4,05**		**Σw = 3.7**	

Evaluation of Proposed Solutions with Table

Each of the proposed design solutions has been evaluated. Each design criterion is compared and scored 0-4.

Clearly, the possible design of the Moving Nozzle Thrust Vector Control Systems scored more points than any other possible design. It was decided to do the Movable Nozzle Thrust Vector Control System.

2.2. Mathematical Model the System

2.2.1. System Dynamics

The rotational dynamics of a general rigid body of this system is described by Euler's equations. But the system described is not a completely rigid body.

The body is constant, as we have the relative movement of the motor relative to the whole system.

and the dynamics of the engine itself. In the most general case, Euler's equations (Eq.1) were used for the s claim analyzed.

$$I\dot{\omega} = -\dot{I}\omega + M_{atm} + M_{wind} + M_{dis} + M_{TVC} + M_{RCS} - \omega \times I\omega \quad (1)$$

Here M_{atm} ve M_{wind}, represents the external moments acting on our rocket.

M_{TVC} ve M_{RCS} forces, respectively, the draging force and the moments due to the presence of the wind, M_{dis} represents the control torques applied against defects such as fuel bloating.

$$\omega^{\cdot} = I^{-1} + (M_{atm} + M_{wind} + M_{dis} + M_{TVC} + M_{RCS} - \omega \text{ x } I\omega \quad (2)$$

It is designed to analyze the feasibility liteness and effectiveness of the TVC system, which is designed to understand what kind of improvements it can lead to with this study. To do this, the actual state of the prototype in the air is simulated, and the TVC is handled in the attitude holding function. Therefore, assuming the prototype is suspended in the air, the drag on the impact is assumed to be small and is considered negligible.

$$\omega^{\cdot}_x = I_x^{-1} + (M_{wind,x} + M_{dis,x} + M_{TVC,x} + (I_y - I_z)\omega_y \text{ x } \omega_z \quad (3)$$

$$\omega^{\cdot}_y = I_y^{-1} + (M_{wind,y} + M_{dis,y} + M_{TVC,y} + (I_z - I_x)\omega_z \text{ x } \omega_x \quad (4)$$

$$\omega^{\cdot}_z = I_z^{-1} + (M_{wind,z} + M_{dis,z} + M_{TVC,z} + (I_x - I_y)\omega_x \text{ x } \omega_y \quad (5)$$

Since different terms describing the control torques applied by the two control systems are known, they can be written in analytical terms. As it relates to what the RCS system is concerned with, due to the specific placement of the thrusters shown, the given control torques must be reflected on the pitching and deflection axes, since they are aligned with the main axis of inertia. However, theloop-free channel of this s is the only channel where RCS is considered. About the TVC, obviously, the two control torques applied to the pitching and deflection motion are interconnected as they are provided by the same actuator (motor).

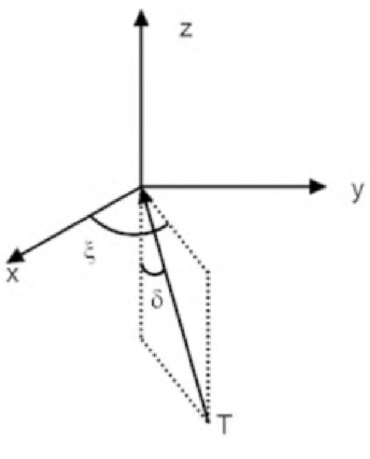


Figure 13: Thrust Vector Spherical Decomposition

where T represents the thrust vector, δ is the gimbal offset angle, and ξ is defined.

gimbal rotation angle. The demonstration usedis given below (Eq. 6, 7).

$-90\ \circ < \xi < 90\ \circ$ (6)

$-\ -5\ \circ < \delta < 5\ \circ$ (7)

ξ is a positive rotation around z.

- ξ = 0 and δ > 0 give a positive pitching moment (moment around it)$y^{\cdot}$

According to Figure 13, the components of the thrust along the three body axesare as follows (Eq. 8, 9).

$$\vec{T} = T \begin{matrix} -sin\delta cos\xi \\ -sin\delta sin\xi \\ cos\delta \end{matrix} \quad (8)$$

S on, the moments acting on the body are as follows:

$$\overrightarrow{M_{TVC}} = Tl \begin{matrix} -sin\delta sin\xi \\ -sin\delta cos\xi \\ 0 \end{matrix} \quad (9)$$

Here l is the distance between the center of mass and the thrust centerof gravity. This coincides with the thrust center gimbal turning point.

2.2.2 Cost function and Riccati equation

With differential equations, the system can be written in the form of aset of linear equations in the form of a space state (Eq. 10).

$$x^{\cdot} = A_x + B_u \quad (10)$$

where x and u represent the state vector and the input vector, respectively. These two matrices A and B are referred to as state matrix and input matrix. This set of equations is usually complemented by the output equations (Eq. 11, 12).

$$y = C_x + D_u \quad (11)$$

$$J = \frac{1}{2}\int_0^x (x^t Qx + u^T + Ru)dt \quad (12)$$

Q and Rare square diagonal matrices in sizes (n×n) and (m×m), respectively. where n is the length of the state vector and m is the length of the input vector (Eq. 13-18).

$$H = x^T Qx + U^T Ru + \lambda^T (Ax + Bu) \quad (13)$$

$$u = -R^{-1} B^T \lambda \quad (14)$$

$$\lambda^{\cdot} = S^{\cdot} x + S(A - BR^{-1} B^T S)x \quad (15)$$

$$- S^{\cdot} = SA + A^T - BR^{-1}B^TS + Q \tag{16}$$

$$u(t) = R^{-1}B^TS(t)x \tag{17}$$

$$K_{opt} = R^{-1}B^TS \tag{18}$$

We see that the solution of the Riccati equation provides the optimal control law, which must be formulated in such a way as to minimize the cost function. Not always, the solution of the Riccati equation is not always possible, but onlyexists under certain conditions. The conditions mentioned in the literature are as follows.

1) $Q \geq 0$ ve $R > 0$

2) The pair (A, C) is observable

3) The pair (A, B) can be checked

These conditions need to be mentioned because they indicate a weakness.

Although the quaternion notation parameter has several advantages, a linear model based on the exact probability of the four components cannot be precisely controlled, which makes it impossible to implement a classical LQR control. However, it has been shown that a reduced pattern of quaternioncan also be handled. K is a system that is controlled by considering only three vectorsl components of the uternion. We will examine this reduced quaternion model in the form of a subheading.

2.2.3 Reduced quaternion model

Let's use theequations of non-computational attitude kinematics by accepting Quaternion as the scalar component of the quaternion q_4 and simply construct the vectorial part of the q quaternion (Eq. 19, 20).

$$q^{\cdot} = \frac{1}{2}\Omega^{\cdot}q + \frac{1}{2}q_4\omega b \tag{19}$$

$$q^{\cdot}_{A^{\cdot}} = -\frac{1}{2}\omega_b^T\vec{q} \tag{20}$$

In this formulation it has been shown that there is a one-to-one mapping between ω and $q^{\cdot}$, for which

It can be replaced by a set of nonlinear attitude kinematics equations that can lead to a linear dynamical system based on quaternion (Eq. 21-23).

$$\omega = 2\Theta^{-1}q^{\cdot} \tag{21}$$

$$\Theta = \begin{bmatrix} f(q) & -q_3 & q_2 \\ q_3 & f(q) & -q_1 \\ -q_2 & q_1 & f(q) \end{bmatrix} \tag{22}$$

$$f(q) = \sqrt{1 - -q_1{}^2 - q_2{}^2 - q_3{}^2} \tag{23}$$

Basically, what is done is to formulate in terms of the 4th kuternion component statement and the other three components. However, the mapping between ω and q˙ occurs only when Φ= π/2 is not case (Eq. 24, 25).

$$\begin{bmatrix} q^{\cdot}{}_1 \\ q^{\cdot}{}_2 \\ q^{\cdot}{}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} f(q) & -q_3 & q_2 \\ q_3 & f(q & -q_1 \\ -q_2 & q_1 & f(q \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ q\omega_3 \end{bmatrix} \tag{24}$$

$$\mathrm{I}\,\vec{\omega} = \mathrm{u} - \vec{\omega} \times \mathrm{I}\,\vec{\omega} \tag{25}$$

where u = $[u1, u2, u3]^T$ represents the vector of control torques on the body axis, applying Taylor expansion to this given formulation we derive the final linear reduction work quaternion model, and by going through h stubs, we can obtain the final expression of the linear equation as follows (Eq. 26)

$$\begin{bmatrix} \omega^{\cdot} \\ q^{\cdot} \end{bmatrix} = \begin{bmatrix} 0_3 & 0_3 \\ I\ \ 3 & 0_3 \end{bmatrix} \begin{bmatrix} \omega \\ q \end{bmatrix} + \begin{bmatrix} I^{-1} \\ q0_3 \end{bmatrix} u = Ax + Bu \tag{26}$$

With this inference, it is fully controllable and solves the typical problem of full quaternion dynamics.

The derived model can show us much more useful results when a linear analysis is performed in terms of quaternion. However, as explained earlier, the evaluation of the behavior of the TVC system in this study is that the prototypeperforms a contro led landing while performing a landing.

2.3. Mechanical Design of the System

During the mechanical design phase, many issues such as manufacturability, cost, mechanism stability, precaution against problems that may occur during the thrust guidance phase are examined. In the process up to the final design stage, it is aimed to make the most perfect design with all revisions. 2 Power HD Mini Copper Gear Analog servo motors integrated into the system make angular movements according to the data coming from the gyro sensor. The 2 shafts connected with the help of the 25T servo arm move the part at the output of the rocket motor thrust vectorally. In this way, the thrust coming out of the nozzle is directed in a vectorial way. Also, while producing prototypes, compliance with engineering standards was also checked.

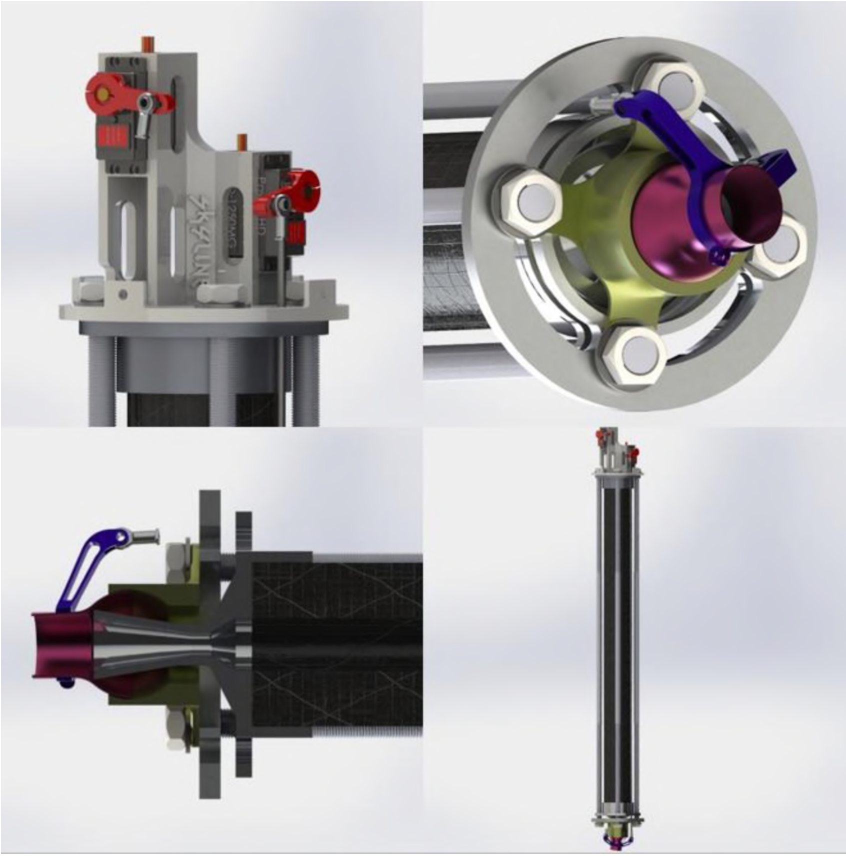


Figure 14: TVC CAD Modeling

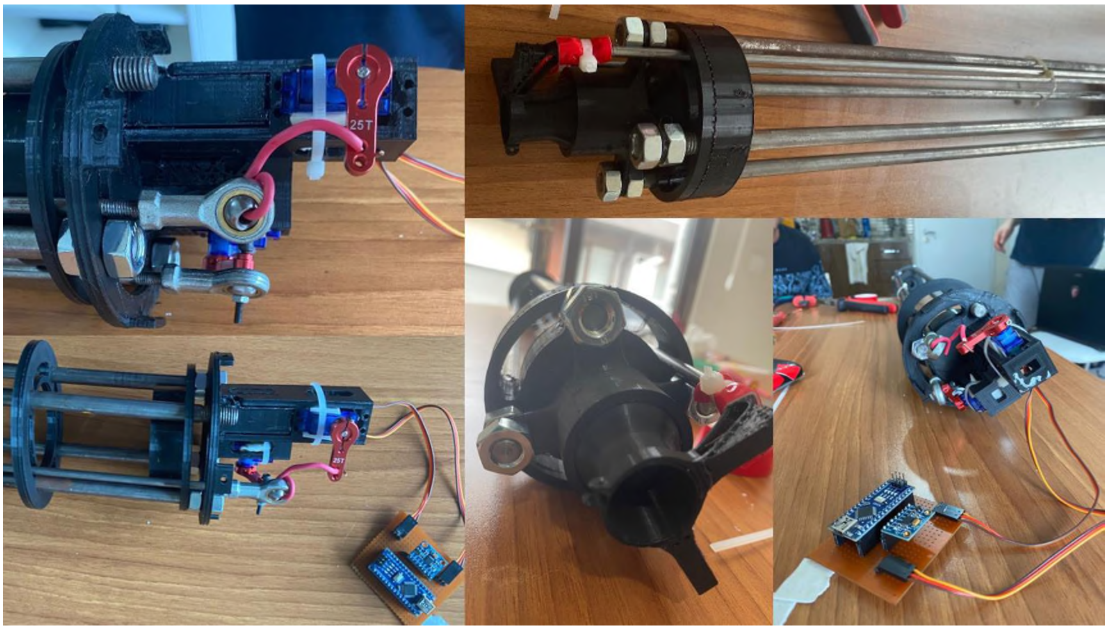


Figure 15: Prototype of the system

3 Results and Conclusions

In this study, a propulsion guidance system (TVC) was developed to be used in innovative low-altitude rockets that would use solid-fuel engines. This study, which is at the conceptual level, was produced and mechanical experiments were made. The next step in this work is to conduct experiments with a real solid-fuel rocket engine and analyze more consistent data. Today's rockets use conventional guidance systems. However, in the coming years, it is foreseen that this system will develop in order to grow space and aviation, to spread space tourism, and to obtain more stable rockets in the defense industry. Therefore, as one of the next studies, it is aimed to make a hybrid rocket-powered cargo or a rocket capable of carrying people to be used entirely in space tourism.

4 Declarations

4.1 Study Limitations

None.

4.2 Acknowledgements

Authors: they would like to thank Sakarya University of Applied Sciences, the SKYLINE Team and TÜBİTAK for their support in their studies.

4.3 Funding source

TÜBİTAK 2209-A, Project number: 1919B012102469

4.4 Competing Interests

There is no conflict of interest in this study.

4.5 Authors' Contributions

Corresponding Author Haktan Yağmur: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review, taking responsibility for the creation of the entire manuscript.

Can Bayar: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review, taking responsibility for the creation of the entire manuscript.

Sinan Şen: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review, taking responsibility for the creation of the entire manuscript.

Kasım Serbest: Developing ideas for the article, planning the methods to reach the results, taking responsibility for the creation of the entire manuscript.

References

[1] Buschek, H. (2003). Design and flight test of a robust autopilot for the IRIS-T air-to-air missile. Control Engineering Practice, 11(5), 551–558.

[2] https://arc.aiaa.org/doi/abs/10.2514/3.1597?journalCode=aiaaj , Accesed: 10.07.2021.

[3] https://en.wikipedia.org/wiki/Thrust_vectoring , Accesed: 15. 07.2021.

[4] https://dergipark.org.tr/tr/download/article-file/438514 , Accesed: 15. 07.2021.

[5] https://core.ac.uk/download/pdf/19143575.pdf , Accesed: 20. 07.2021.

[6] https://www.researchgate.net/publication/323685633_Design_and_Implementation_of_a_Thrust_Vector_Control_TVC_Test_System , Erişim Tarihi: 20. 07.2021

[7] Lazic´, D. V., & Ristanovic´, M. R. (2004). Thrust vector control of twin nozzle engine. Proceedings of the VIII triennial international SAUM conference (pp. 94–97). Belgrade, Serbia, November 2004.

[8] Schinstock, D. E., & Haskew, T. A. (2001). Transient force reduction in electromechanical actuators for thrust-vector control. Journal of Propulsion and Power, 17(1), 65–72.

[9] Skogestad, S., & Postlethwaite, I. (1996). Multivariabile feedback control. England: Wiley.

[10] Ünal A., Yaman K., Okur E. ve Adlı M.A., "Design and implementation of a Thrust Vector Control (TVC) test system", Politeknik Dergisi, 21(2): 497-505, (2018).

[11] Song, C., Kim, S. J., & Kim, S. H. (2006). Robust control of the missile attitude based on quaternion feedback. Control Engineering Practice, 14(7), 811–818.

[12] Zipfel, P. H. (2000). Modeling and simulation of aerospace vehicle dynamics. Reston, VA: American Institute of Aeronautics and Astronautics, Inc.

[13] https://www.esa.int/ESA_Multimedia/Images/2008/11/The_thrust_vector_control_system_of_the_Zefiro_23_engine_part_of_the_Vega_launcher_was_developed_under_GSTP

[14] Wie, Bong. "Thrust vector control analysis and design for solar-sail spacecraft." Journal of Spacecraft and Rockets 44.3 (2007): 545-557.