Explainable Neuro-Symbolic Ontological Evolution for Anatomical Feature Synthesis in 6G-Enabled Tele-Surgery

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Abstract

This project proposes a new framework for the autonomous robotic surgery medical atlas, focusing on a self-modifying ontological system. Using Neuro-Symbolic (NeSy) integration, this research resolves one of the major challenges relating to anatomical and morphological anomalies in the context of real time tele-surgery. Current deep learning based models provide good capabilities for performing models (as well as understanding the models), unfortunately, they do not provide the required interpretability, and consistent, logical, and incremental/basic reasoning that can hold in a critical medical intervention. This project proposes a system involving the concept of synthesising a new anatomical symbol when a new unforeseen, and, in the context of the symbolic models of the architecture, highly atypical structure of the patient is documented in the context of surgery. The system does this justification to the medical expert in the context of the architecture through the Explainable (and) XAI over the low/or ultra low latency 6G telecommunications. Using the combination of topological data analysis with the Blockchain based Federated Learning, this research guarantees that the surgical intelligence system is both adaptive and dynamic, as well as secure and of a provable (formal) trust across the distributed medical networks..

Keywords: Neuro-Symbolic AI, Explainable AI, Ontological Evolution, Anatomical Feature Synthesis, Medical Image Synthesis, Knowledge Graphs, Semantic Reasoning, Digital Twin, Remote Robotic Surgery.

3. Problem Statement

The most significant current constraint to the development of autonomous surgical assistants is the “Rigidity of Representation.” Most current systems run on fixed ontologies—an agreed-upon lexicon of anatomical constituents. In the context of tele-surgery over the upcoming 6G networks, the presence of an “out-of-distribution” anatomical constituent (for example, an atypical vascular configuration) is both a perception and reflective of failure. “Deep” neural networks provide “black-box” classifications which, in surgery, lack the rigor of accountability. There is a high demand for a system to:

1.Identify anomalies through advanced manifold learning.
2.Justify normative and new categorizations of tissues through XAI.
3.Generate and Disseminate novel categorizations into a comprehensive and secure medical logical system.

4. Research Objectives

- Designing an XAI module focused on fuzzy logic that provides real-time explanations for image tissue classification during medical image assessments.

- Formulating a model that incorporates the Riemannian Manifold for Autonomous Ontological Expansion to discover and encapsulate additional anatomical constructs.

- Establishing a Byzantine secure cross-border transaction and surgical intelligence sharing Secure Blockchain/6G Consortium/Collaborative Surgery to ensure a secure cross-border transaction and surgical intelligence sharing.

5. Proposed Research Papers (Methodology)

Paper I: Attentional-Fuzzy XAI for Explainable Surgical Segmentation

- Focus: This paper highlights the importance of transparency regarding Surgical AI. This paper also introduces a Mixed Approach, where Neural Attention Maps (NAMs) are filtered by the Sugeno Fuzzy Integrals to linguistic statements (e.g. “Malignant Margin identified with 92% confidence due to textural irregularity”).
- **Mathematical Approach:**

$$E_{\mu}(f)=\bigvee_{i=1}^{n}[f(x_i)\wedge\mu(A_i)]$$

- Submission Targets (Q2 SCI): Journal of Medical and Biological Engineering, Informatics in Medicine Unlocked, International Journal of Fuzzy Systems, Biomedical Signal Processing and Control.

Paper II: Riemannian Manifold Regularization for Anatomical Symbol Synthesis

- Focus: The objective of this paper is to supply the workings of how a robot can 'name' an unfamiliar anatomical structure. Persistent imaging features which don’t fit the current ontological structure would be detected, and a new logical thread would be instantiated by treating the image space as a high-dimensional manifold.
- **Mathematical Approach:**

$$\min_{f}\sum_{i=1}^{l}(f(x_i)\text{-}y_i)^2+\gamma\|f\|_K^2+\lambda\int_{\mathrm{M}}\|\nabla_{\mathrm{M}}f\|^2dp$$

- Submission Targets (Q2 SCI): Computerized Medical Imaging and Graphics, Medical & Biological Engineering & Computing, International Journal of Computer Assisted Radiology and Surgery, Journal of Healthcare Engineering.

Paper III: Secure Decentralized Evolution via 6G and Blockchain

- Focus: Much of the recent findings are attributed to more extensive collaboration of working methods. New "discovered" methods of sharing Medical findings will ensure this collaboration is fruitful. Dr.Elango aims to collate the use of 6G and Blockchain to suggest a solution that preserves /secures patient data to authenticate novel anatomical symbols.
- Mathematical Approach: Geometric Median Aggregation for Byzantine-robust updates.

$$w_{t+1}=GeometricMedian(\{w_t^1,w_t^2,\ldots,w_t^n\})$$

- Submission Targets (Q2 SCI): Journal of Network and Systems Management, Peer-to-Peer Networking and Applications, Intelligent Service Robotics, World Wide Web Journal.

Anatomical Feature Synthesis

Anatomical feature synthesis refers to generating or reconstructing missing, hidden, incomplete, or patient-specific anatomical information.

Input

- CT images
- MRI images
- Ultrasound
- Endoscopic images
- Robotic camera streams

Synthesized Features

- Organ boundaries
- Blood vessels
- Nerves
- Tumor regions
- Tissue layers
- Anatomical landmarks
- 3D structures

Expected Contributions

1. A neuro-symbolic framework for anatomical feature synthesis.
2. Dynamic ontological evolution for representing patient-specific anatomical variations.
3. Explainable AI mechanisms that improve surgical decision transparency.
4. Real-time anatomical knowledge integration using neural and symbolic reasoning.
5. A 6G-enabled architecture supporting low-latency tele-surgical communication.
6. A framework for synthesizing incomplete or hidden anatomical structures while maintaining clinical knowledge constraints.

Suggested Evaluation Metrics

Anatomical Synthesis

- Dice Similarity Coefficient
- Intersection over Union
- Accuracy
- Precision
- Recall

Symbolic Explanation

"The structure was identified as a hepatic vein because its spatial position, connectivity, and relationship with the liver match the anatomical ontology."

Sample Experimental Dataset

Assume that both methods are evaluated on **1000 anatomical feature samples**.

Metric	Deep Learning	Proposed ENS-OE
Correctly synthesized features	850	920
Incorrect features	150	80
Explainable decisions	620	910
Anatomically consistent features	860	950
Contradictory features detected	60	78
Average latency	42 ms	30 ms
Successful surgical-context matching	820	930

Accuracy Calculation

Method	Correct	Total	Accuracy
Deep Learning	850	1000	85%
Proposed ENS-OE	920	1000	92%

Improvement:

92−85= 7 % points

Relative improvement:

92−85×100=8.24%

Method	Average Latency
Deep Learning	42 ms
Proposed ENS-OE	30 ms
Latency reduction	28.57%

Overall Comparison Table

Evaluation Metric	Deep Learning	Proposed ENS-OE	Improvement
Feature synthesis accuracy	85%	92%	+7 pp
Anatomical consistency	86%	95%	+9 pp
Explainability	62%	91%	+29 pp
Surgical-context matching	82%	93%	+11 pp
Contradiction detection	60/100	78/100	+30%
Average latency	42 ms	30 ms	28.57% lower
Incorrect features	150	80	46.67% reduction

The proposed Explainable Neuro-Symbolic Ontological Evolution (ENS-OE) method demonstrates better performance than conventional deep learning because it combines:

Neural Learning+Symbolic Reasoning+Ontology Evolution+Explainability

The most significant improvement is in explainability (62% → 91%), while anatomical consistency improves from 86% → 95%. The reduction in latency from 42 ms to 30 ms also makes the proposed approach more suitable for latency-sensitive 6G-enabled tele-surgery.

Role of 6G in Tele-Surgery

6G can provide the communication infrastructure required for intelligent tele-surgical systems.

Important Requirements

- Ultra-low latency
- High reliability
- High bandwidth
- Edge intelligence
- AI-native communication
- Digital twins
- Holographic visualization

Conclusion

The novelty of this work lies in integrating explainable neuro-symbolic learning with dynamically evolving anatomical ontologies to synthesize patient-specific anatomical features, while leveraging 6G edge intelligence for low-latency and knowledge-aware tele-surgical assistance.

It combines AI, medical imaging, knowledge representation, Explainable AI, and next-generation communication systems.

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